University of Nevada, Reno

Automatic Detection of Stains on Lidar Glass Houses and Notice for Cleaning

A thesis submitted in partial fulfillment of the
Requirements for the degree of Master of Science in
Civil and Environmental Engineering

by

Shradha Toshniwal

Dr. Hao Xu / Thesis Advisor

May 2021

THE GRADUATE SCHOOL

We recommend that the thesis
prepared under our supervision by

SHRADHA TOSHNIWAL

entitled

Automatic Detection of Stains on Lidar Glass Houses and Notice for Cleaning

be accepted in partial fulfillment of the

requirements for the degree of

MASTER OF SCIENCE

Hao Xu, Ph.D., Advisor

Zong Tian, Ph.D., Committee Member

Richard Kelly, Ph.D., Graduate School Representative

David W. Zeh, Ph. D., Dean, Graduate School

May, 2021

ABSTRACT

For achieving a sustainable and smarter transportation system, sensor technology needs to be combined with transportation infrastructure. Traffic sensors are significant in today's world since the conventional visual inspection is inadequate for steering quality control and traffic safety, efficiency being of utmost importance, high-speed and accuracy automated inspection becomes crucial. No system is perfect, and Lidar is no different.

Although Lidar, sensor has gained its popularity with its 360-degree monitoring and visualization, being a relatively new technology, it has its frail spots too. Mainly, on roadside, factors like surface obstacles or environmental condition, influence its performance with uncertainty of cloud point movement from its true value.

Therefore, through this study, a standard method based on the difference of offset is proposed to check the quality of data for real road deployment and answer a very foundation question from traffic engineering, about the obstacles recognition on lidar glass houses, and how often to clean the sensor increasing confidence on such systems .

In this study, multiple experiments, comparing different conditions of sensor surface was conducted where real time frame was compared to standard frame and the frame offset was used to define a threshold value and over threshold offset time. The experiment was conducted with varied beams, scenarios and further the method was validated with real time traffic data. Sensor itself may have many cavities; we only needed to know the limiting range to accommodate real traffic. This study therefore contributed by developing method to find out influence of stain on sensor automatically and notify related agency, the time to clean the sensor without validation from engineers at intersections at every small interval.

ACKNOWLEDGEMENTS

The completion of this study was not possible without the support of several people. With endless love and appreciation, I would like to extend my earnest gratitude to the people who helped me during this research.

I would like to express the deepest appreciation to my thesis advisor Dr. Hao Xu, who has the attitude of a leader. His expertise, direction, and instructions helped me flourish during my journey at the Transportation Engineering program at University of Nevada, Reno (UNR). I am also very happy and gratified that, I got to work with him on other research projects that made my background very assorted and gave me involvement in various challenging topics.

I would also like to express my appreciativeness and truly gratefulness to Dr. Zong Tian, for his constant supervision, reassurance, and boundless support during the two years of study.

I would like to express the sincere appreciation to Dr. Richard Kelly for serving as a member in my Thesis committee.

I would like to express my heartfelt thanks to Eng. Hemant Sapkota for helping to make this study a well-done achievement.

My special thanks to all my contemporaries and friends at this program, for their inspiration and ethical support which made my stay at UNR more pleasing.

Finally, I must express my very deep appreciativeness to my family. I want to give main gratitude to my parents, spouse and my child for providing me with unfailing support and unceasing inspiration throughout my years of study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

The growth and expansion of any country are closely tied to, improvements in nation's transportation system. Different statistics from past to present, clearly exemplify, the strong need of improvement in safety and efficiency in the transportation sector. As per the recent data and estimates from, U.S. Department of Transportation, the annual economic cost of crashes is $242 billion with a total of 36,096 motor vehicle deaths / crashes in 2019 [1]. Not only safety becomes an issue, problems like congestion have triggered and surpassed now and then. According to a report by the Texas Transportation Institute, in the United States, commuters spend approximately 42 hours stuck in traffic in a year. This not only distresses the consumption of time of the consumer but vice versa have a nationwide influence, wasting more than 3 billion gallons of fuel, with a price tag of $160 billion, almost equivalent to $960 per commuter [2]. Even, prior statistics holdup the same fact, with an instance in the United States, from 1987 to 1997 where highway miles traveled increased by 33 percent, while public road mileage increased by less than 2 percent worsening congestion [3] [4]. The increase in demand, relative to the limited construction of new roads, has caused such issues in the United States and throughout the industrialized world. Being unobservant with the downsides associated, addition of facilities is always measured as a comeback and a resolution.

Thus, a substitute to expensive new construction was required, which would promote more efficient utilization of current transportation facilities and was initiated through, Intelligent Transportation Systems (ITS), that encompassed a large area in transportation sector including electronic surveillance, communications, traffic analysis and control technologies resulting traffic management, safety to transportation system users and managers [5].

1.1 Brief Overview of Sensors in Transportation and Challenges Associated

Traffic Sensors are promising technology offering solution for design and development of a good deal of traffic control system applications consisting of a sensor and gateway nodes [6]. The calling of node guarantees traffic monitoring, gaging physical traffic parameters like flow, density, volume, headway, waiting time. Whereas, gateway node collects the traffic information and guides equivalent to base station.

Initially sensors were employed for signalized intersection control, but now they stream real-time data for traffic adaptive signal control and reduce recurring congestion. The relative comfort is, sensor performance reports are provided with convenient access to public and private libraries for better traffic management strategies. The commercial way of mobility service and transportation has changed with facilities like MaaS (Mobility as a Service) like Uber and Lyft, and TaaS (Transportation as a Service). Sensors convey a massive part of it and are being applied, either in vehicle or on roads [7].

One of the main challenges faced by intelligent transportation systems, is the monitoring range of sensing device reduces, being located on the roads, vehicles, and transportation infrastructures getting affected by various external factors. Optical stability is mainly affected, even if dirt or water clings to sensor lens but being mounted on exterior surface this becomes a challenge. Environmental parameters both rain and fog turn as reflectors and produce missed alarms during stain detection. Glint from sunlight results unwanted and confusing signals. Atmospheric particulates and inclement weather can scatter or absorb energy that would otherwise reach the focal plane [8].

According to S. Hasirlioglu et al.'s research, the relationship between temperature and visibility is in inverse proportion during foggy weather [9]. In lower temperatures, the fog causes more loss of the detecting range of the laser sensors [10]. Besides the undesirable impact on the environment, exhaust from the automobiles also have an effect on the performance of the obstacle detection technology.

Additionally, current sensing systems are faced with damaged infrastructure, sensor reachability problem, blurry or erased transit lines. Processing of large amounts of real time traffic data, the run time and reliability are the difficulties to be solved to guarantee real-time demand of the urban traffic management system through sensors. Even packet loss can happen at changed phases and sensor can malfunction or breakdown.

These are some of the general issues with numerous optical sensors but according to their type i.e. roadside or on vehicle, the sensors vary with the characteristics, applications, pros and cons, specific issues related with them.

1.2 Roadside Sensors

Traffic data collection using instruments along the roadside, has become one of the important parts for intelligent transportation systems. State and Federal reporting requirements like vehicle detection, incident detection, commercial, and emergency information services are delivered through traffic sensors on roadside. Cameras, video image processing, microwave radar, laser radar, magnetometer, and inductive loop sensors are implemented on roadside, by governmental institutions to collect data about environmental and traffic conditions.

Roadside sensors are classified as Intrusive or Non-intrusive sensors based on their location [11]. Intrusive sensors (in roadway sensors) are most used in traffic control systems and are installed on pavement surfaces. Whereas non-intrusive (over roadway sensors) are installed over different places on the roads, as for example mast-mounted, bridge mounted or across roadside and provide many of the intrusive sensors' functions with fewer difficulties technologies. [12].

Although have high accuracy, in roadway sensors, are correlated with high fitting and maintenance costs. Passive magnetic sensors, pneumatic tube sensors, inductive loops, piezoelectric sensors are widely used intrusive sensors in terms of traffic related applications.

1.2.1 Inductive Loop

This sensor is one of the most widely used sensor in traffic management. It consists of a long wire coiled, to form a loop which is installed into or under the surface of the road and measures the change in the electrical properties of the circuit when a vehicle passes over the sensor, producing an electrical current [12].

The technology of inductive loop has good performance on detecting volume, presence, occupancy, speed, headway, and gap and is very mature. The price of loop sensors is less, but some downsides are associated with it. Under rain, poor pavement surface condition worsens the situation since water penetrates in the saw-cut resulting detector failures.

Challenges related with maintenance

Being very delicate to the installation process, these detectors must be reinstalled every time a road is repaved, they can only be installed in good pavement. Disrupting traffic, damage to the road surface, safety risk to the installers are some of the drawbacks associated with installation and maintenance of in-roadway sensor.

1.2.2 Magnetic Sensors

It contains of a coil of wire enfolded around a magnetic core but moreover acts in much of the same way as an inductive loop detector. Both vehicle presence and passage detection can be executed through it. Change in the magnetic field caused by the passage of a vehicle is measured through it. The advantage of both types of magnetic detectors (active and passive) is that they can be used, where small-area location of vehicle is essential. They have large detection range and for observing multiple lanes of traffic, this tends to be one of the best solutions. One of their disadvantages is that multiple detectors need to be installed to detect smaller vehicles.

Challenges related with maintenance

Though these sensors, they can give accurate volume counts, being intrusive and are known to be affected by extreme weather conditions. Temperature change and extreme air turbulence can have an impact on its performance.

1.2.3 Piezoelectric Sensor

The piezoelectric sensor can be flushed with the pavement consisting of a long strip of piezoelectric material. The detector detects presence of a vehicle, only if the vehicle has stopped, although these are considered very accurate. These sensors are line detector perpendicular to the path of the vehicle and have the advantage of indicating exactly when and where a vehicle passed by.

Challenges related with maintenance

A drawback associated is that, for a permanent installation, they must be embedded in the pavement. The sensor needs to be replaced with every time pavement is paved, or if a pothole appears.

1.2.4 Pneumatic tube Sensor

When a vehicle passes over these tubes send a burst of air pressure and produce an electrical signal which is further transmitted to the processing unit. It uses one or several tubes placed across traffic lanes allowing for number of vehicles counting and vehicle's classification [12]. For permanent and temporary data recording both, it has good portability. The accuracy of these detectors is questionable and gets low when, truck and bus volumes are high because of the physical characteristics of these vehicles.

Challenges related with maintenance

The only major problem linked is it is easily influenced by weather.

Non-intrusive sensors (over roadway sensors) are installed at different places on the roads and could detect a vehicle's transit and other parameters such as vehicle speed, and lane coverage. Recent evaluations have shown that modern over-roadway sensors produce data that meet the requirements of many current freeway and surface street applications [12]. Climatic conditions such as: snow, rain, and fog highly affect over roadway sensors. The non-intrusive sensors are as follows:

1.2.5 Video cameras

These sensors are placed at the roadside to collect and analyze images from a traffic scene to determine the changes among successive frames using traffic parameters such as flow volume and occupancy [12]. For freeway sites, video detection techniques are considered highly reliable in comparison to urban areas. The primary advantage of video detection is the wide range of data it can provide like volume, presence, occupancy, density, speed and classification, other data such as vehicle identification, incident detection, and origin destination information can be obtained.

Challenges related with maintenance

VIP are vulnerable to bad weather conditions, shadows, and reflections from the roadway surface and give reduced performance. Lighting, wind, precipitation, are various environmental factors that affect the video detection performance. More maintenance efforts are required to assure reasonably good performance. Some of the major problems that affect VIP are, inclement weather, shadows, vehicle projection into adjacent lanes, occlusion, day-to-night transition, vehicle/road contrast, shaking of camera by wind, and water, salt, dirt, grime on camera lens. One of the factors that reduces flexibility of utilization of VIP is the height restriction, as cameras need to be typically mounted at heights of 50 to 60 feet.

As for instance, 1998 report to the TRB Freeway Operations Committee, the New York State Department of Transportation (NYSDOT) stated that one VIP model had difficulty detecting vehicles on a roadway lightly covered with snow in good visibility. Similarly, a 2004 evaluation of VIP performance by Purdue University described significant false and missed vehicle detections as compared with loops, even when the cameras were installed at vendor-recommended locations at a well-lighted intersection [5].

1.2.6 Radar Sensors

Low-energy microwave radiation is transmitted by radar sensors and is reflected by all objects within detection zone. There are different types of radar sensor systems: (1) Doppler systems that use the frequency shift of the return to track the number of vehicles, and determine speed very accurately, (2) frequency-modulated continuous wave radar radiates continuous transmission power such as a simple continuous wave radar and is used to measure flow volume, speed, and presence [12]. In general, the good features of these are easy installation and accuracy. They also support multiple detection zones with operation during day or night. Short range (24 GHz) radar applications enable blind spot monitoring, lane-keeping assistance, and parking aids, whereas long range (77 GHz) radar sensors include automatic distance control and brake assistance [13].

Radar systems typically have no trouble at recognizing substances during fog or rain unlike camera sensors. Through their range-finding ability radar devices can intellect the presence of motionless vehicles and sense multiple zones.

Challenges related with maintenance

Their main disadvantage is high susceptibility to electromagnetic interferences.

1.2.7 Infrared Sensors

Such sensors can be mounted on sides of road and overhead configurations and can be operated during both day and night. Energy generated by vehicles is detected by the sensor and converted to electrical signals and finally to the processing unit. They are divided into two categories: Passive Infrared detects vehicles based on emission or reflection of infrared radiation and are used to collect data from flow volume, vehicle presence and occupancy.

Active Infrared sensors use Light Emitting Diodes to measure the reflection time and collect data on flow volume, speed, classification, vehicle presence, and traffic density. The main advantage of infrared devices is that they can cover multiple lanes simultaneously [12].

Challenges related with maintenance

Air conditions may influence the reflection of the infrared beam and thus these detectors are sensitive to inclement weather conditions and ambient light. They require periodic lens cleaning and lane closure for maintenance.

1.2.8 Ultrasonic sensors

Ultrasonic sensors calculate the distance between two objects based on the elapsed time between a sound wave transmitted at frequencies between 25 and 50 KHz and reflected to the sensor by an object. The received energy is converted into electrical energy which is sent to the processing unit [12]. Data about vehicle flow and the vehicle's speed are collected through these sensors. They are mounted directly overhead or from a side-fire position, these devices can provide surveillance on multiple lanes providing equitably accurate counts.

Challenges related with maintenance

The main disadvantage of this kind of sensors is its high sensitivity to environmental effects.

1.3 On Vehicle Sensors

1.3.1 Camera

Vehicles equipped with cameras provide a larger picture of road traffic conditions around upholding 360° view of their exterior setting. These image sensors automatically detect objects, classify them, and determine the distances between them and the vehicle [13].

Challenges related with maintenance

The camera sensors in the automobiles, are still distant from being faultless. Rain, fog, or snow, such poor weather situations can stop cameras from clearly sighting the complications in the roadway, increasing the chances of collisions. Additionally, there are often conditions where imageries from cameras simply aren't adequately decent for a sensor to make a good verdict about what the car should do [13]. There are real time incidents which clarifies these instances.

As for example, 2004 survey conducted by the Urban Transportation Monitor contained responses from 120 jurisdictions. The survey results were summarized that 66% of respondents indicated that they would increase their application of video detection while 12% indicated that they will decrease their applications [5]. Most frequent negative replies had to do with the incapability of video detection to provide satisfactory results (or any results at all) during inclement climate (fog, heavy snow) and when the sun shines straight at the camera.

1.3.2 Ultramagnetic and electromagnetic sensors

Ultrasonic sensors can identify how far-off the vehicle is from said body using echo-times from sound waves and get the driver conscious when the next vehicle gets closer.

Whereas, electromagnetic sensors create an electromagnetic field around the bumper, and offer an alert whenever objects enter it [13].

Challenges related with maintenance

Environmental conditions such as temperature change and extreme air turbulence can influence the performance.

1.3.3 Lidar

Lidar stands for light detection and ranging, and it is most often used to create high-resolution 3D point-clouds, mapping the surroundings to create a full 360-degree map. These sensors are well-known for, their association with autonomous vehicles. To ensure passenger safety, it can be integrated into the sensing system of self-driving passenger cars.

Although Lidar systems has always been expensive and cumbersome, the use of it dates back since the 1990s for commercial purposes, and the technology dates to 60s [14]. Lidar is changing the world because it bridges the gap between the digital and physical.

In mid-1980s, the lack of consistent marketable global positioning system solutions for sensor aligning presented holdups for further development. Companies that offered ground GPS survey services and equipment, commenced evolving with new airborne kinematic GPS solutions.

By the mid-1990s, producers of laser scanners were distributing Lidar sensors that could send 2,000 to 25,000 pulses per second to clienteles who intended to use them for topographic mapping applications. Though primitive by today’s standards, these devices were delivering compressed data sets, which could not be achieved by ground survey. Lidar featured data that were generally formed by photogrammetry.

In the last 20 years, Lidar has significantly changed with firing 1 million points per second within 5 mm accuracy. Technological revolution in Lidar has catapult the development of the Lidar. The application of Lidar has impacted the social, health, environmental and economic spheres of human life. The major areas where sensors are being used in the worldwide market are:

- Environmental mapping and automobile safety are two application segments where Lidar is immensely used.
- Access to Lidar has the ability to create 3D representations of existing space and build digital plans on the real spaces for construction teams. For instance, art historian, Andrew Talon, saw the mapping of Notre Dame in exact detail using a Leica laser scanner which after the great fire in 2019 was immediately turned up as a safe road map for restoration. The availability of LiDAR mapping thus has saved heritage site from the dustbin of history [14].
- It has an important usage in agriculture and forestry, to determine the best ways to increase crop productivity, along with determining impact of human activities on forests.
- Not being limited to that, it proves its usage in mining applications, determining material volumes in open pit mines, as well as exposure to risks.

- It can provide scans of different areas to assist city planners with blueprints. As an archetype, Lidar scans of the 12th-century Cambodian temple complex Angkor Wat revealed whole swaths of previously unidentified roadways, canals, urban areas, temples delivering new insights into the history of the Khmer Empire [14].
- These scanners were used for disaster inspection, ageing facility inspection, remodeling progress inspection. A superior contribution was, after the Earthquake of 2011, in the Great East Japan base map data could be provided to the earliest, by surveying large affected areas quickly with high-density scans, using 3D scanners and increasing the operational efficiency [15].

The reason that the number of Lidar applications has ballooned in recent years, multiple Lidar scans are made and sewed together in an alignment which accelerates the scan registration by 40%-80%, and removed the need for manual oversight process. In 2019, Shenzhen Urban Transportation Planning and Design Research Center took the lead in applying the RS-LiDAR-V2R for use in city roads for Didi's Cooperative Vehicle Infrastructure System

Although various advantages of Lidar technology have come upright, it is paired with some faults that challenge this technology and its interface. Before discussing the difficulties associated, there is a need to have a thorough knowledge of elementary terms related with this sensor.

Cloud points: Lidar are also called laser scanners as it uses time-of-flight measurements to gauge distances with pulse lasers. These can fire up to 1 million pulses per second in a sweeping pattern, each point striking the closest line-of-sight object [14]. Light that is reflected to the scanner is thus measured and a distance is calculated based on the speed of light. Each of these points is arranged and together is processed as a ‘point cloud’ to produce a highly detailed 3D image.

Surface obstacle: Sensors typically look at the world through a relatively small fixed lens. One challenge, after being installed, is the lens of the sensor, that is when a sensor’s view of the world becomes obscured, through water or dirt or a single bug splat, in the environment. This makes it tough for the scanner to differentiate between a real object beyond the Lidar, and elements that are right on the Lidar window [16].

When the system is launching photons over hundreds of meters, trying to capture an overview, the raked lens bounces back returning light off in all directions prompting hindrances, and ensuing miss or false detection, such obligation on surface of Lidar lens are categorized as surface obstacle.

Noise: Noise are irregular fluctuations that accompany a transmitted electrical signal but are not part of it and tend to obscure it. It is simply produced as an unwanted by-product of other activities and can block, distort, or change the meaning of a message in both human and electronic communication.

Noise basically leads to anomaly and deviates something from normal, standard, or expected. For an example, rain can be considered as a periodic noise [17]. A Lidar sensor usually performs the detection of targets, and measures characteristics of those through laser beam propagation, energetic modeling of the received signals, geometry of the illuminated objects. Different weather condition or environmental obstacles limit the field of view degrading the powers of reflection, diffraction, absorption, resulting noise.

Challenges related with maintenance

It is much more expensive than radar sensors and another problem is that snow or fog can sometimes block lidar sensors and negatively affect their ability to detect objects in the road. The Chinese Academy of Social Sciences reported that issue of haze and fog in northern China has become furthermost serious problem since 1961 [18]. Due to the coal-powered heating systems and low standard of vehicle emissions, the visibility was below 50 m in Harbin during the worst periods [19].

Experiments were conducted in both real foggy environments and simulation laboratories, which proved that sensors like Lidar and vision cameras had trouble in accurately scanning driving environment and surroundings to some extent [20]. An experiment using a smoke machine was conducted, which showed glycerol and oil-based evaporation weakened the performance range for LIDAR sensor [9].

Although these are reviewed as on vehicle technology, these can be used for roadside detection too, so it becomes an important part of the study. As an archetype, sensors like Lidar can convert vehicle data into information about vehicle and pedestrian trajectory, showing how vehicles slow down, stop, speed up and go through an intersection during a light cycle.

1.4 Problem Statement and Objective of Study

Every ITS system requires different frequency of maintenance, due to the variance in location, city, weather, environment, technology etc. Mainly, on roadside, factors like surface obstacles or environmental condition, influence performance of the sensors. In both extreme weather conditions (rain, snow, fog) and some specific situations in urban areas, although quite advanced, the current technological developments are not sophisticated enough to guarantee 100% precision and accuracy of obstacle detection.

Specially in case of Lidar, because if its glass surface, and no good protection in the outer shell, it gets easily influenced by different factors making the accuracy or reliability questionable. Accurate traffic data is of utmost importance to make informed decisions to improve traffic conditions. Beyond the threat of being condensed from fog and road spray that can prove as difficult to remove quickly as solid material, a significant concern for lidar surfaces is being knocked out by dirt, and road debris. In such cases, validation would always be required through associated traffic agencies or engineers. Maintenance requirements, such as camera lens cleaning, lane closures at night and traffic diversion for installing or repairing in-roadway sensors could be a part of the process with an uncertainty in the regularity of upkeep required.

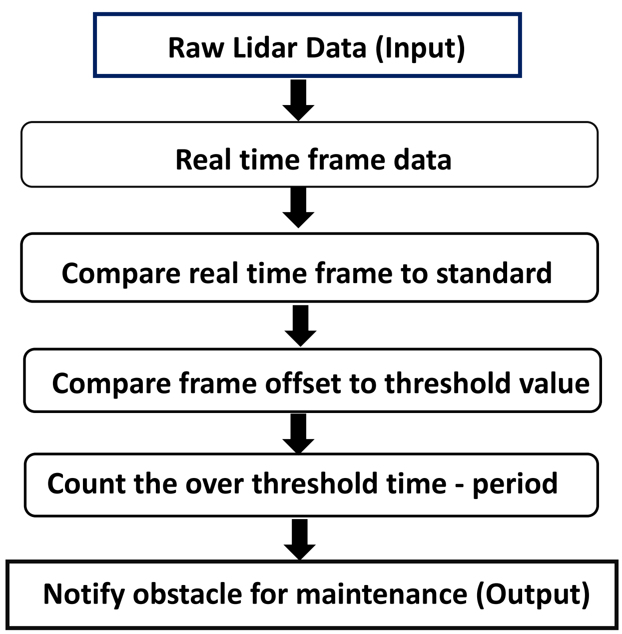


Figure 1: Outline of the Study

The primary objective of this research is to provide automatic method to trigger engineers or agency, the precise time to clean or maintain the sensor. Thus, this method can answer a very foundation question from traffic engineering, as to when we should maintain the Lidar sensor on roadside. It would provide a standard notification and would avoid checking or maintenance from engineers at intersections at every small interval.

This technique can thus increase confidence on such systems and the data processed and solve problem of how often to clean the sensor. In addition, this effort also led to development of, malfunction detection of Lidar sensor even before its installation.

CHAPTER 2. LITERATURE REVIEW

If maintenance is not provided, even with greater design and installation, systems do not function as envisioned for protracted periods. Therefore, scheduled, and regular sensor maintenance helps prolonged procedure of traffic signal control systems and management systems.

2.1 Maintenance of Road Sensors

The maintenance of sensors, include fully burdened costs for technicians to prepare the road surface or subsurface (for inductive loops or other surface or subsurface sensors), install the sensor and mounting structure, purchase and install conduit, close traffic lanes, divert traffic, provide safety measures where required, and verify proper functioning of the device after installation is complete [5]. These devices are either installed in, below, or above the roadway. Making installation and maintenance for over-roadway sensors is relatively easy, even being compacted and mounted above or to the side of the roadway. Some relative issues associated, over-roadway sensors are sometimes prohibited in certain locations and when existing structures are not available.

Based on different operating technologies there are cost differences in maintaining sensors. The sensor-cleaning, maintenance topic is fundamentally price driven. Maintenance and life cycle costs may be determined, in part, by published values of the mean time between failures. Some over-roadway sensors are designed with mean time between failures of 64,000 to 90,000 hours.

Thus, maintenance and replacement costs for these devices may be significantly less than for inductive loops over a 10- year period, especially if commercial vehicle loads, poor subsoil, inclement weather, and utility improvements frequently require road resurfacing and loop replacement.

Adherence to appropriate installation and upkeep procedures, can definitely reduce the incidence of failure and the number of needless maintenance calls. For example, the passage-detecting magnetometer detector, with its limited application, has managed to hold popularity with minimum maintenance. The improved reliability and functionality in inductive-loop detector electronics units have shifted the main sources of loop detector failure to the wire loop in the pavement.

2.2 Sensor Maintenance Research and Practices

Globally or for States no such guidelines are present for maintenance of sensors whereas a comprehensive reference document is provided in coordination with FHWA, to aid the practicing traffic engineer, planner, or technician in selecting, designing, installing, and maintaining traffic sensors for signalized intersections and freeways from Lawrence A. Klein called Traffic Detector Handbook [8].

Installation and maintenance require traffic needs to be managed, in accordance with "Part 6—Temporary Traffic Control," as found in the Manual on Uniform Traffic Control Devices (MUTCD) [21]. Design engineers and those responsible for installation and operations should be fully aware of the cause-and-effect relationship between their activities and maintenance issues. Sensor maintenance issues have changed considerably over the years, those which formerly accounted for a considerable portion of malfunctions, has matured to the point where many currently available digital models seldom experience failure.

2.3 In Roadway Sensors

2.3.1 Inductive Loop

The analysis of a malfunctioning inductive-loop detector can be a difficult task. The root cause of the failure may be associated with environmental conditions or other factors attributed to installation. The technician analyzing a faulty inductive-loop system should consider all causes of failures.

The hostile street environment makes the loop wire most vulnerable component of an inductive-loop detector system. Therefore, a scheduled visual inspection of the roadway at and around sawcut should be conducted every 6 months to determine if the integrity of the pavement, sealant, or slot has been violated. The inspection should include looking for wires that have floated to the top of the sealant. Loops with exposed or shallow-buried wires needs to be replaced. Unstable, cracked or deteriorating sealant should be removed with a blunt instrument. The slot should be blown clean with compressed air and new sealant poured over the old. This is especially important in areas where snow removal equipment is used, and salt applications are prevalent.

When visual inspection does not immediately disclose the problem, systematic troubleshooting is required. An experienced technician is frequently able to pinpoint the troubled area or faulty part by visual examination. Procedures for identifying and correcting malfunctioning inductive-loop detector systems are discussed below.

A. Operational Check of Malfunctioning Detector

Several operational checks can be conducted to expedite analysis of malfunctioning inductive-loop detector system. These checks can be performed utilizing a maintenance vehicle and a vehicle simulator that analyze adjacent lane detection, motion in the loop wire, intermittent detection, and sensitivity of the loop system [8].

- Adjacent Lane Detection

At locations where adjacent lane detection is suspected, one technique is to maneuver the maintenance vehicle close to the lane and monitor the electronics unit. The sensitivity is then adjusted so that the maintenance vehicle does not cause an output.

- Intermittent Operation

To identify this problem, the operation of the inductive loop is observed while the maintenance vehicle is driven over the various loops suspected of having intermittent operation. Another approach to identifying sources of intermittent operation is to visually inspect all connections and test them with a 500-volt megger and a low-ohm midscale ohmmeter.

- System Sensitivity

A simulated vehicle that represents the smallest detectable vehicle can be used to determine if the inductive-loop system sensitivity is in balance and to determine the minimum sensitivity required of the system. The same procedure can also be used to test new installations. The simulated vehicle is utilized to measure change in inductance, which is a measure of the sensitivity. For this purpose, a frequency reading is made with no vehicle present; then the simulated vehicle is introduced into the detection area and a new frequency reading is taken. The difference between the two frequencies provides a measure of the change in inductance.

B. Sequential Test Procedure

The six steps described below assist in isolating the causes of inductive- loop detector system malfunction.

Step 1. Conduct Visual Inspection

Check for indication of broken or cut loop or lead-in wires. Check for open leads within the controller and for the connection of the power source to the electronics unit.

Step 2. Check Operation of Inductive-Loop Electronics Unit

To eliminate the electronics unit as the source of the problem, replace the existing unit with one having a known sensitivity. If the operation is not considerably improved, remove the substituted unit, replace the original unit.

Step 3. Measure Parameters Needed to Determine Quality Factor Q

Measure and record the following data on the quality factor data form. With the electronics unit disconnected and power removed from the loop, measure the resistance from either loop terminal to the bus or conduit ground. With the loop test meter attached to the controller tie points and the electronics unit disconnected, measure the inductance of the loop system.

Step 4. Determine Q

To determine the Q of the loop system, follow the procedure described below and record the results on the quality factor data form:

Attach the Q test unit to the existing cable or adaptor cable as required. Connect ac voltmeter and digital frequency counter to the Q test unit to read loop voltage and frequency in kHz. Adjust frequency for maximum voltage across the loops; record the frequency as fr and the voltage across the loops as Elps. Successively increase and decrease the frequency to obtain the frequency points having 70 percent of the resonant voltage value. Record these as higher fh and lower fl. Calculate and record the bandwidth BW and Q, where BW = fh – fl and Q = fr/BW [8].

Measure Sensitivity of Inductive-Loop System. Perform the analysis by comparing the measured values for each of the items with the reference table. Determine required maintenance from suggested Corrective Actions [8].

2.3.2 Magnetic Sensors

Magnetic detectors have an extremely good maintenance record. As they are installed under the road surface and all lead-in wires consist of cable encased in underground conduit, the opportunity for failure is relatively small. Some of these devices have been installed for more than 20 years without a failure.

In the rare case where a magnetic detector fails, the first step is to examine the electronics unit. When false responses occur (the electronics unit output relay closes when no cars are crossing the detection area), the existing unit needs to be replaced with another tested unit, tune, and monitor. If the system then works, it can be assumed that the original unit was at fault. If the system still does not work, a series resistance test followed by a resistance-to-ground test is required [8].

- The total circuit resistance-to-ground of the detector should be measured after disconnecting all the jumpers to ground and the leads to the relay. In cases where leakage is between detector cables and signal cables, proper cable layout and good splicing can avoid this condition.
- If the voltmeter needle moves erratically when there are no vehicles passing the probes, it generally indicates surges in nearby power wires. If the probe can be located closer to traffic, the sensitivity of the electronics unit can be decreased to reduce the effect of power lines. Changing the orientation of the detector axis can eliminate or minimize the effect of a particular power line
- If line voltage changes are suspected of causing the voltmeter needle to behave in an erratic manner, the "Magnetic Detector Plus" and the "Magnetic Detector Minus" leads, needs to be disconnected. If the voltmeter needle is still erratic, the trouble is due to line voltage changes. In this case, examine the power service connections to make sure they are properly soldered and insulated. If there are no obvious problems, the power company checks the regulation of the power being supplied and makes any necessary modifications to their equipment.
- Fluctuations on the neutral power wire with respect to ground might also cause intermittent response. A connection to a conducting rod driven into the ground (required in most modern installations) can stabilize this condition.
- Other problems could involve induced voltage response, which can occur when the detector leads are placed in the conduit with the power supply leads. Induced voltage can cause false responses. Consequently, lead-in cable should not be inserted into conduit with another signal wiring [8].

2.4 Over Roadway Sensors

2.4.1 Video Cameras

Periodic cleaning of the camera lens is the most pervasive maintenance operation for video image processors. The cleaning regularity differs from six months to one year, depending on the characteristics of the monitored area, camera mounting height, the truck traffic volume, and precipitation and dust. Cleaning may be contracted or performed by the agency responsible for traffic management. Specialized boom trucks are required for cameras mounted on the tallest poles (e.g., (21 m). In some cases, like for over-roadway sensors lane closures are required for bucket trucks to be parked on the mainline. This disrupts road traffic posing a safety risk to the installers. Staffing concerns related to numbers and skill levels of maintenance personnel needs to be realistically maintained by available agency personnel or local contractors.

2.4.2 Radar Sensors

Radar sensors do not appear to require much maintenance. For an instance, EIS Electronic Integrated Systems Inc., the manufacturer of the RTMS, reports that of 624 units shipped to one North American client, 10 (or 1.6%) were returned for repair from April 1994 through June 2002 [8].

2.4.3 Infrared

A rule of thumb for gauging when an infrared sensor may have trouble detecting a vehicle in inclement weather is to note if a human observer can see the vehicle under the same circumstances. If the observer can see the vehicle, there is a high probability the infrared sensor will detect the vehicle.

2.5 On Vehicle Sensors

2.5.1 Cameras

Digital cameras have featured ultrasonics to remove dust and dirt from internal surfaces since Olympus introduced the feature in 2003. Ultrasonic cleaning works well on sensors because of their relatively small area to clean. The technology employs piezo electronics (PZT) to generate an ultrasound frequency of around 35 kHz. Rather than pressure-washing the dirt with a liquid jet, a thin film of water or cleaning fluid is applied. The vibration of the lens transfers the dirt into the fluid. It then atomizes the fluid from the surface, taking the dirt with it [22]. It is the most effective mechanism for removing surface crud from a sensor. A challenge with using ultrasonic PZT actuators is in determining how hard the actuator needs to be driven for effective cleaning, difficult to accommodate many different sensor geometries; need for a large fluid tank on the vehicle, and addition of multiple wiper systems [22].

2.5.2 Lidar

Keeping lidars clean is crucial to the operation of an Autonomous Vehicle (AV). It's a technical challenge that has the industry engaged in finding solutions.

Valeo and Continental are among industry suppliers that have developed fully automatic cleaning systems for AV lidars and cameras. The technologies typically use retractable liquid-jet nozzles that spray a precise amount of cleaning fluid (stored in an onboard reservoir) onto the sensor lens or face. Some include drying and de-icing heaters [22].

LiDAR, Innoviz One, is a new technology that is designed with a blockage algorithm that enables the sensor to recognize if there's a loss in availability or degradation of performance due to loss of light passing through the obstacle [23]. This unique sensor can classify the different types of blockage to use the right cleaning scheme, such as cleaning with water spray, air pressure, heating, etc. Finally, based on input coming from the vehicle, the sensor can decide whether to continue to function with limited availability or to enable the cleaning.

Ford's 'tiara' sensor suite funnels air out through slots near the sensor lens, deflecting debris, the air flowing out of the tiara pushes it aside, so it doesn't contact the lens. In addition to choosing the correct cleaning solution, there is also a need to decide when best to apply it [24].

2.6 DOT's and Their Maintenance Issues

Illinos Department of Transportation [23]

In Chicago, IL, IDOT maintains more than 18,000 inductive-loop detectors. Because of their experience with loop failure, they initiated an active inspection and maintenance program to monitor each loop. This program has reduced replacements to about 35 recuts per year. They report that no more than 5 percent of their loops are inoperative at any given time [4].

Iowa Department of Transportation [23]

Iowa DOT typically does not install only a single pavement sensor on a roadway or bridge deck. There are usually multiple sensors installed, which can be compared to one another. In addition, both bridge and road sensors are attached to an Road Weather Information System station. Slight differences between sensors that are close to one another are expected due to location variation and road direction. However, if there is a more pronounced variation in temperatures, then staff go out and take a reading with a handheld infrared monitor to see if it matches what the pavement sensor is reporting. A lot of Iowa roads are rural enough that they don't need to close roads to use a handheld unit on location.

Minnesota Department of Transportation [23]

Typically, RWIS sensors are embedded flush in the roadway surface. Their installation and maintenance require a lane of traffic be temporarily closed while work is performed. These sensors must be moved if a road is resurfaced or reconstructed. Scheduling work is done during non-peak traffic hours and can be difficult for roadway managers, especially when work is often performed by sensor vendors or specially trained personnel. MnDOT has used data from multiple sources to adjust traffic alerts triggered by embedded sensors.

2.7 Studies Related with Lidar

A. Using huge amount of Road Sensor Data for Official Statistics [25]

Big data is a very interesting, but the quality of the data is a challenge. Most of the time, the quality of each data element in a big data set is poor, which makes it hard to decide on the usability of the data set as a whole. The paper focus on data collected by 20,000 sensors on the Dutch highways, for the period 2010 until 2014 a total of 115 billion records with a volume of 80TB. Although the data is very structured in a technical sense, the content of the data was not that well-structured.

For instance, in 98% of the sensor data collected daily, at least 1 minute of measurement was missing due to signal loss between the road sensor and the central database. In addition, sensors regularly fail to function and the relationship between the data of adjacent road sensors is not as evident as it should be. Since vehicles pass sensors at different speeds and the sampling frequency is limited to only one sample per minute, one does not find a large correlation between the data of two sensors, even if they are 250 meters apart. Because the arrival times of the vehicles at a sensor fluctuate, the data are very erratic: the number of vehicles passing a sensor at a particular minute strongly differed from the number of vehicles passing subsequent minutes.

Through this paper, a cleaning process was developed, that removed the high frequency component in the data and was able to fill in the gaps induced by missing data. Smoothing the signal by removing high frequency components increased autocorrelations. This also increased cross correlations between adjacent sensors, due to a decrease in the variance of the data. It was assumed that (i) vehicles arrived independently at a road sensor, (ii) one vehicle did not alter the probability distribution of another vehicle and (iii) two vehicles could not pass a road sensor at the same time. Hence the observation noise was modeled by a Poisson distribution.

B. A study on Recent Development and Issues with Obstacle Detection Systems for Automated Vehicles [17]

This paper reviews critical issues with obstacle detection systems for automated vehicles. The current review looks at technology and existing systems for obstacle detection. According to the World Health Organization, in 2015, there was a total of 1.25 million traffic accidents, 270,000 people fatalities, resulting in over 700 life losses each day on average. It was reported that over 90% of crashes were based on driver error. To improve this situation, governments, car manufacturers and municipal departments have considered a large amount of investment to support the development of various technological solutions.

The focus of this work is to discuss current developments and existing technologies for obstacle detection that can make autonomous driving safety possible in the near future. Discussions were on how different technologies perform in different situations during daytime or at night

Radar: Performs mapping at medium to long range. Better than cameras and LIDAR in the worse weather possible, but lacks the fine resolution required for object identification.

Lidar: Provides 360-degree high-resolution mapping, from short to long range. Limited by harsh environments with low reflective targets.

Ultrasound: Low cost and shows good performance in short-range measurement. Suitable for parking assistant in parking lots due to its fast response in a relatively short range.

Camera: Provides a complete picture of the environment in a variety of situations, as well as able to accurately read road signals and color buttons, but are limited by the visibility conditions within the driving environment

Infrared (IR): Gives excellent support for night vision among all sensors. LIDAR can also be used during nighttime because of its capabilities to work in low-visibility environments

Combining different technologies gives a more accurate detection, surveillance and recognition of the driving environment and all surroundings, including vehicle and pedestrian, lane, and other objects; but, still, further effort is required to develop more precise sensor fusion system.

Like human drivers, the autonomous vehicles (AVs) must ensure a continuous observation of the driving environment and all surroundings. Five key elements are involved: the obstacle, the road, the ego-vehicle, environment, and driver. Amongst these, the obstacle with its different properties, size, shape, weight, material, frequency of appearance is the most significant element to focus on. To provide AVs with the abilities to detect an obstacle and obtain information about its properties, sensors are integrated and installed in and around the vehicle. This paper highlights the advantages of Lidar over other sensors.

The laser path and reflection rate on material surface changes of LIDAR performs well in rainy environments with rain intensity lower than 20 cm difference.

C. Lidar Sensor Simulation in Adverse Weather Condition for Driving Assistance Development [26]

This research project fills the need by developing testing methods for pavement sensors and it seeks to establish guidelines for practical testing methods that will evaluate whether the pavement sensor is providing an accurate representation of actual conditions at the installed site

In this project, the authors used their findings to automate the process of identifying malfunctioning weather sensors in real time. The authors analyze the weather data reported by various sensors to detect possible anomalies. Their interface system allows users to define decision-making rules based on their real-world experience in identifying malfunctions. Since decision rule parameters set by the user may result in a false indication of a sensor malfunction, the system analyzes all proposed rules based on historical data and recommends optimal rule parameters. If the user follows these automated suggestions, the accuracy of the software to detect a malfunctioning sensor increases significantly. This report provides an overview of the software tool developed to support detection of sensor malfunctions.

D. A hybrid defect detection method for compact camera lens [27]

When several types of defects exist in an inspection region, the most efficient approach is to treat each type of defect separately. This study proposes, an automated inspection method for camera lens for identifying problems like circular texture and the non-fixed position of the inspection region and getting the issues resolved through Hough transformation, weighted Sobel filter, and polar transformation. The method developed is thus divided into four steps: (1) locating a circular inspection region, (2) polar coordinate transformations, (3) candidate defect detection, and (4) the SVM classification method. This enables real defects to be identified for an accurate detection result.

If the circular inspection region can be converted into a rectangular one, the defect detection problem can be substantially reduced, and a real defect can be easily detected. The equation for converting between Cartesian and polar coordinates is defined as follows

$x=a+r\cos\theta y=b+r\sin\theta$

where (x, y) is the position in the circular inspection region and the range of θ is 0−360 degree. Through polar coordinate transformation, the circular texture changes to horizontal texture.

According to the manufacturer's specifications, the areas of regions that are smaller than 0.01 mm can be ignored. To compute the gradient while reducing the effect of the texture, a weighted Sobel filter is used with two weights, Wx and Wy, that are added to the vertical and horizontal components of the gradient, and most textures are noted as being horizontal.

Many small and narrow edges remain in the gradient image, and these edges are too small to be defects. to remove these noise-like edges morphological operations are applied, opening and operations are combination of erosion and dilation operation.

To enhance remaining edge regions and remove small gradient edges, a thresholding method is applied. Only larger gradient values are considered candidate defects, because defects always accompany a high contrast in the local region. To identify the location of the candidate defective region, watershed segmentation method is applied. The idea is that if the distance to nearby candidate regions is too small, these candidates belong to the same candidate defective region. Centroid points of each candidate defective region are located by averaging all coordinates of the pixel in a defective region.

While the candidate defective regions were detected, the features were extracted from candidate defective regions for recognition of real defect regions using classification method. The main idea of this method is trying to find the optimal separating hyperplane by maximizing the margin between the hyperplane and the data.

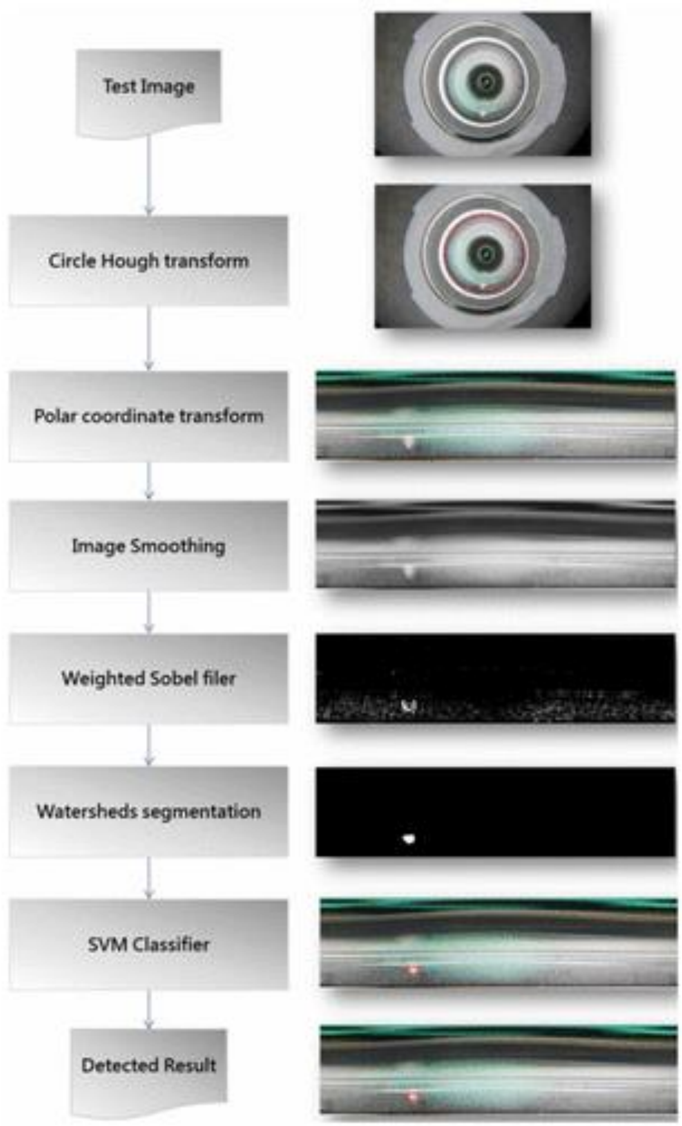


Figure 2: Flowchart of Proposed Defect Detection Method for Compact Camera

2.8 Findings from Literature Review

Varied literatures and studies were used for getting a comprehensive knowledge about sensors. Although all these studies are not directly related with the scope of work, but they have given a background or foundation to know the basics of sensor, their data processing and analysis of results. After reading all the literatures and studies, it clarifies sensor performance can be influenced by varied factors, such as environmental parameters like fog or snow, temperature, weather or some obstacle like dust or debris. But the research gap is, the influence of the stains is not quite well studied in sensors except camera, which might result in degraded data quality. Thus, these sensors being positioned on roadside, it is very important for related agencies to know when to clean or maintain their sensors. So that's why, my research will focus on automatic detection of those stains and notification for cleaning.

The study of camera although, prompted a concept for automatic detection of defective region, but no actual guideline is present, as to when the sensors should be maintained, at what time, what should be the frequency to get the real time traffic data. Especially in case of Lidar, although it has been very advantageous in autonomous vehicles, its use on roadside have not been much touched upon. Some papers are present about it but analyze very limited data. The justification of data associated with it, validation and maintenance has not been there in any literature or guidelines. This pushes the lifecycle costs, operating issues, technical people to make untimely visits to check the sensor and its functioning. Studies even talked about anomaly seen with sensor data but the automatic measures for finding the influence and timely maintenance, which can reduce cost and cause operation efficiency of Lidar is not put on.

Even testing methods are developed by researchers for pavement sensors for accurate representation of actual conditions, but in case of Lidar, being a new but versatile technology not much exploration has been executed. In autonomous vehicles for safe perception system, Innoviz one, lidar has developed blockage algorithm but that says which cleaning method to be used, but does not put about frequency of maintenance required, which will also start its production in 2021.

Our purpose is to put Lidar sensor on roadside for long term. When sensors are installed on roadside, we have no idea, the data is influenced by time or not. This is the current knowledge gap. For real road deployment my method helps to check the quality of data and give qualitative data. In other words, my study fills this gap and develops a method using real time traffic data collected through Lidar and verifies the malfunction or obstacle, and alarms engineers about the frequency of maintenance required for roadside Lidar used for collection of traffic information.

CHAPTER 3. METHODOLOGY

3.1 Experimental Plan

Regardless of all the benefits and specifications revealed through the literatures, there is still a need to assess the reliability of the sensor to determine the impact of surface obstacles prior to installation of Lidar and even after implementation on the field, to validate the monitoring and capturing of the terrain and objects. While there is prolific list of purposes, where Lidar is applied, being a relatively new technology, it has its frail spots too. Mainly, on roadside, factors like surface obstacles or environmental condition, influence performance with uncertainty of cloud point movement from its true value. Therefore, through this study an automatic method would be developed that triggers a warning to the engineers when obstacles are detected on lidar glass houses, reaching a predefined threshold, and notifies the frequency of maintenance required.

This study followed the procedure of first analyzing the data of intersection and getting a knowhow of the quality of data and then developing a method for surface obstacle detection and verifying the method for real time traffic data. Three assessments were conducted at an intensely busy intersection of Reno, and a testing facility at University of Nevada Reno (UNR) and for each tryout, a criterion was used, and scenarios were tested. Through this study technologies are not compared, however with same technology different conditions are compared.

Our purpose is to put Lidar sensor on roadside, for longer term. When data is collected, we have no idea, whether the data is influenced by time or not, it is the current knowledge gap. For real road deployment, thus, a real time traffic data collected by the sensor, which in this case is set to be on the intersection of McCarran Blvd and Evans Ave, is used to validate and check the quality of data. The quality of data thus can be affected by various definite reasons like weather, environment, surface obstacles, or sensor itself.

To know the precise reason of the influence and rule out the effect off outside environmental factors, the data needed to be consequently tested in a well-controlled environment. Experiment No. 2, consisted of simulation of different scenarios of varied surface obstacle and used the continuous data of 10 mins for every scenario in a controlled environment of a lab, in Applied Research Facility (ARF) building, in University of Nevada, Reno premises. The different simulated surface conditions (dust, humidity, precipitation, mists) in a controlled environment and smaller area helped checking the actual reason of influence and to ensure which of the factors, are affecting the drift of the cloud points. This analysis accordingly would help to identify a method for automatic detection, which leaded a path for the third and foremost crucial process where the data on road; at intersection would be used to validate this method or model for real time traffic scenario.

Further to finalize, an examination would be carried out at the same intersection, where it initiated with real time traffic data. To justify outputs, this would be a practical test case where results of this study would be compared with experimental results published previously. Experiment No. 3, accommodated traffic influence with some real environmental conditions on the same intersection of McCarran Blvd and Evans Ave using the data of 10 minutes - 6000 frames) from April 2020-January 2021. This eventually would answer the question, how often do sensors surface need to be cleaned when used for traffic data collection.

Figure 3: Lidar being influence by surface obstacle at intersection

3.2 Elements of Experimental Program

Figure 4 illustrates the flowchart of the experimental program. Three major analyses were carried out. Analysis I consisted of a comparison of different days data between April-July considering time as a variable, to see the influence of dust, since dust accumulates in a longer period while analysis II verified pattern of drift or offset of cloud points is consistent or erratic for both experiments and evaluated in the laboratory. The measured performance characteristics and distribution of points were studied and thus would be compared with the recital at intersection with road users.

Finally, the findings from analysis I and analysis II, III of the experiments were used to present the final threshold that could be a point for alarming the engineers to define whether maintenance is required or not.

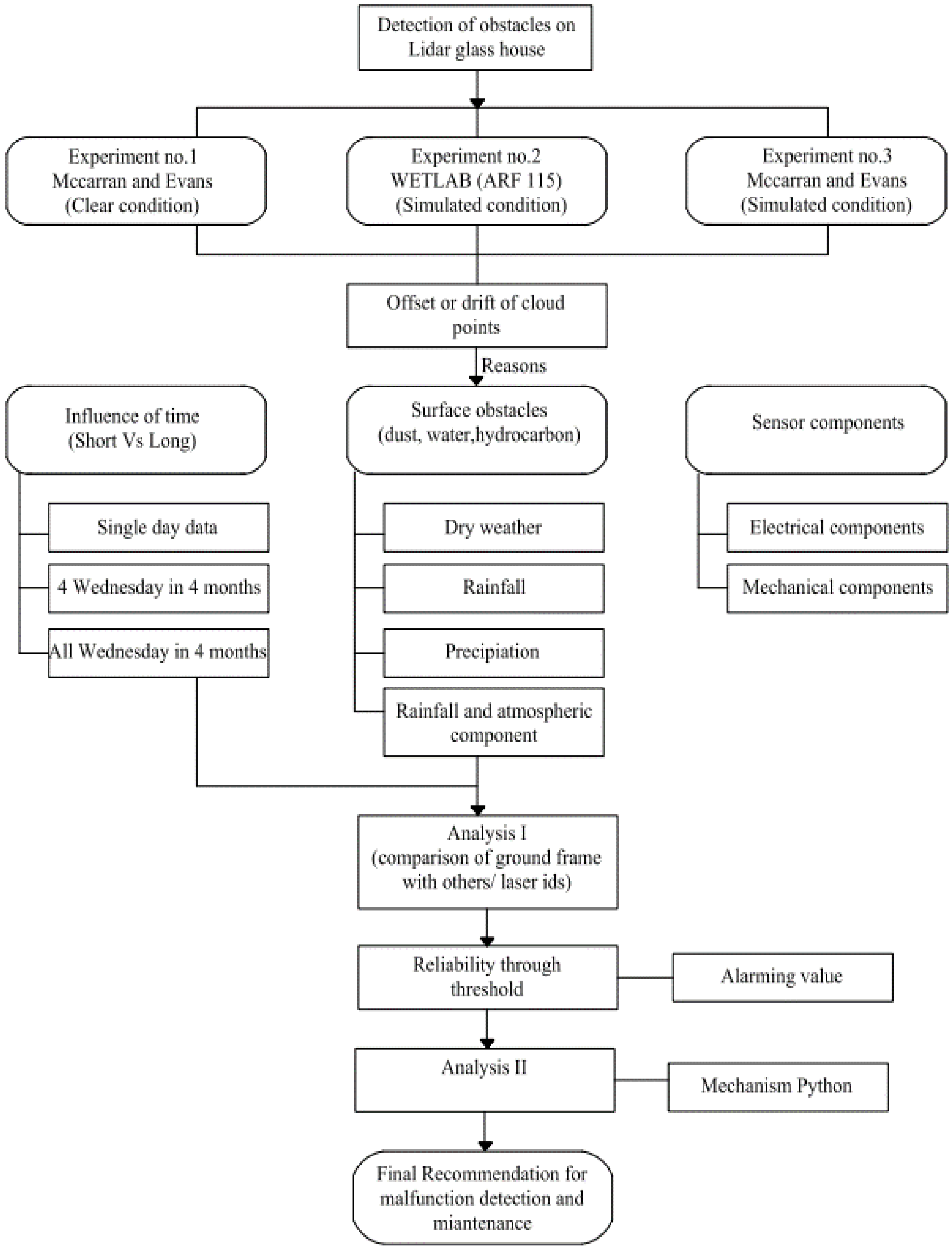


Figure 4: Flowchart describing the procedure of the experimental program

CHAPTER 4. DATA PROCESSING, EXAMINATION AND RESULTS

4.1 Experiment no.1.

4.1.1 Apparatus Setup

Lidar Sensor with 32 channels (VLP-32C) was setup at North East corner of McCarran Blvd and Evans Ave. Real time traffic data was collected and used for this process.

Figure 5: Lidar testing site of McCarran Blvd and Evans Ave

4.1.2 Data Processing

The first method/experiment number 1, analyzed short time versus long time changes in the cloud points captured by Lidar, taking standard or baseline data in clear surface and environmental condition. The data that was used was from April 10 - Jul 31, 2019. The quality of data thus can be affected by various definite reasons like weather, environment, surface obstacles, or sensor itself. Some of them demonstrate immediate effect in short time whereas factors like surface obstacle would take a longer period. If the effect is in short period, it is basically related with sensor but if in long time it must be related with surface obstacle like dust. So, for this, the influence is checked by taking time as a variable, short time versus long time changes, through three steps.

- Checking single day data
- Considering same day data of every month
- Consecutive same day every week until the month of data collected

4.1.3 Analysis and Results

a) Study of single day data

At first, a single day data of 10th April was considered, to analyze streaming and the changes in different times of a day. Data of twenty-three hours is used with frequency of every two hours, that is eight hours data was examined.

Figure 6 shows the cloud points in the real database. Different color here indicates different frames or different times of a day and the circles means different laser beams. The center of X-axis and y- Axis or 0, here represents the position of Lidar. X and Y-axis represents distance of objects from Lidar which is in meter. Figure 7 is an extension of figure 6. Both the figure illustrate, in a day, shift of the cloud points, of the static objects, which in this case needs to be called as offset, nevertheless in due course took place in a patterned manner and at the end of the 21-hour cycle the offset was insignificant, as the cloud point, almost returned to the original position. Streaming in a single day data executed and there were changes in different times in a day, but it was nominal, which could be related to the motion caused in the sensor. To justify this, data of every month was checked further.

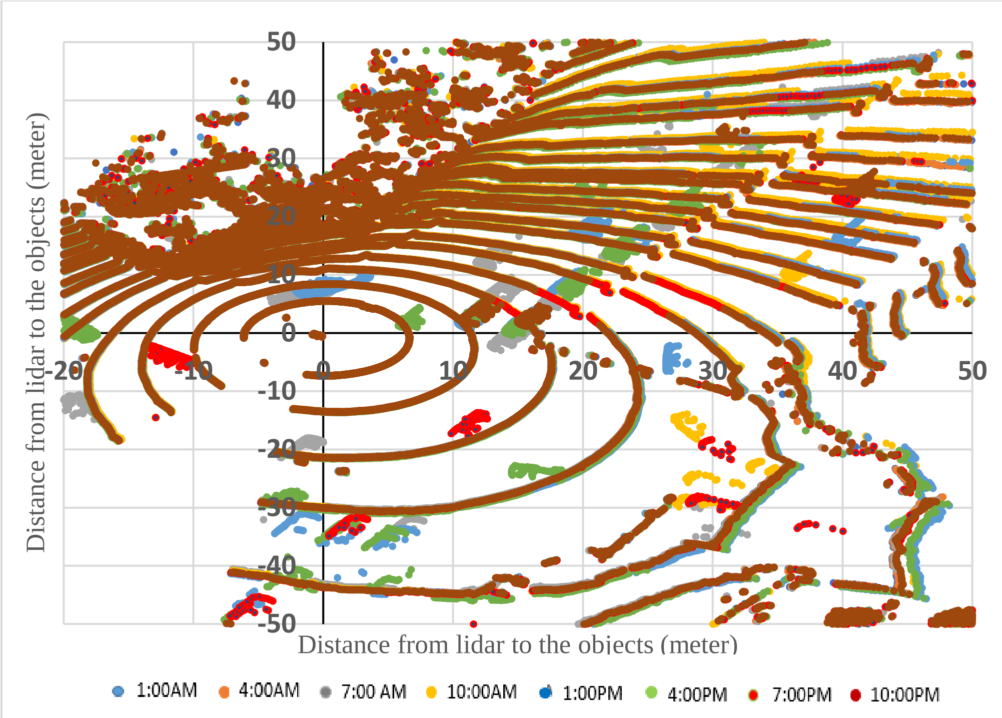


Figure 6: Location of coordinates on single day at different timing

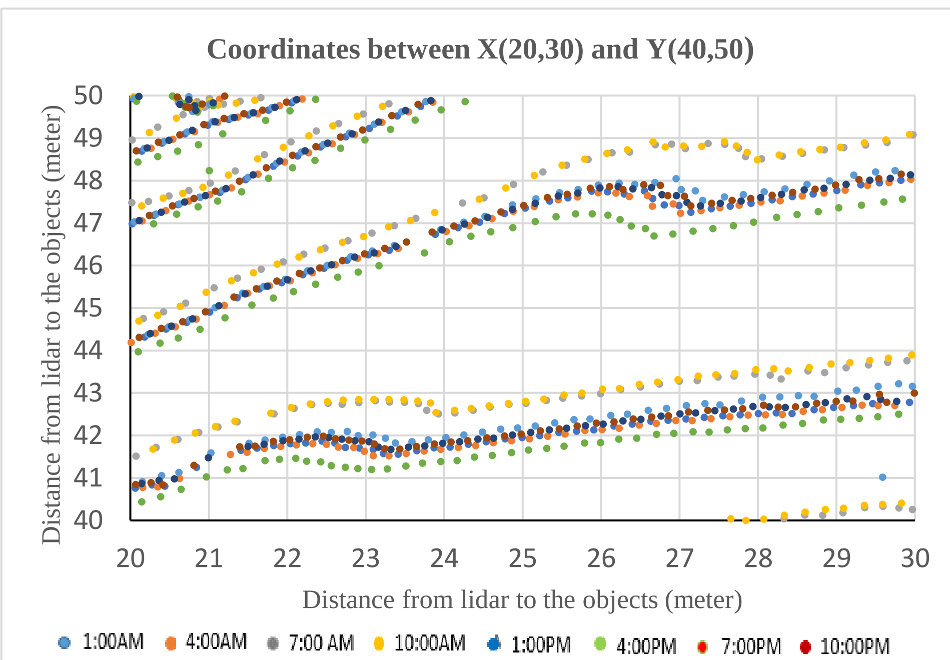


Figure 7: Extension of specific area with offset and variation

b) Considering the same day every month

Since the drift/offset was insignificant in a day, every month same day's data was used to validate this implication. One Wednesday per month from April-July, data of 3rd April, 22 May, 19th June and 17th July was studied to see the changes in the cloud points. Figure 8,9,10 shows change in due course of time. A major drift is seen in some areas was seen, and was greater than 0.5 m. A patterned drift was observed but to be specific, and to check at what point major changes occurred, changes were checked after every week in four months period.

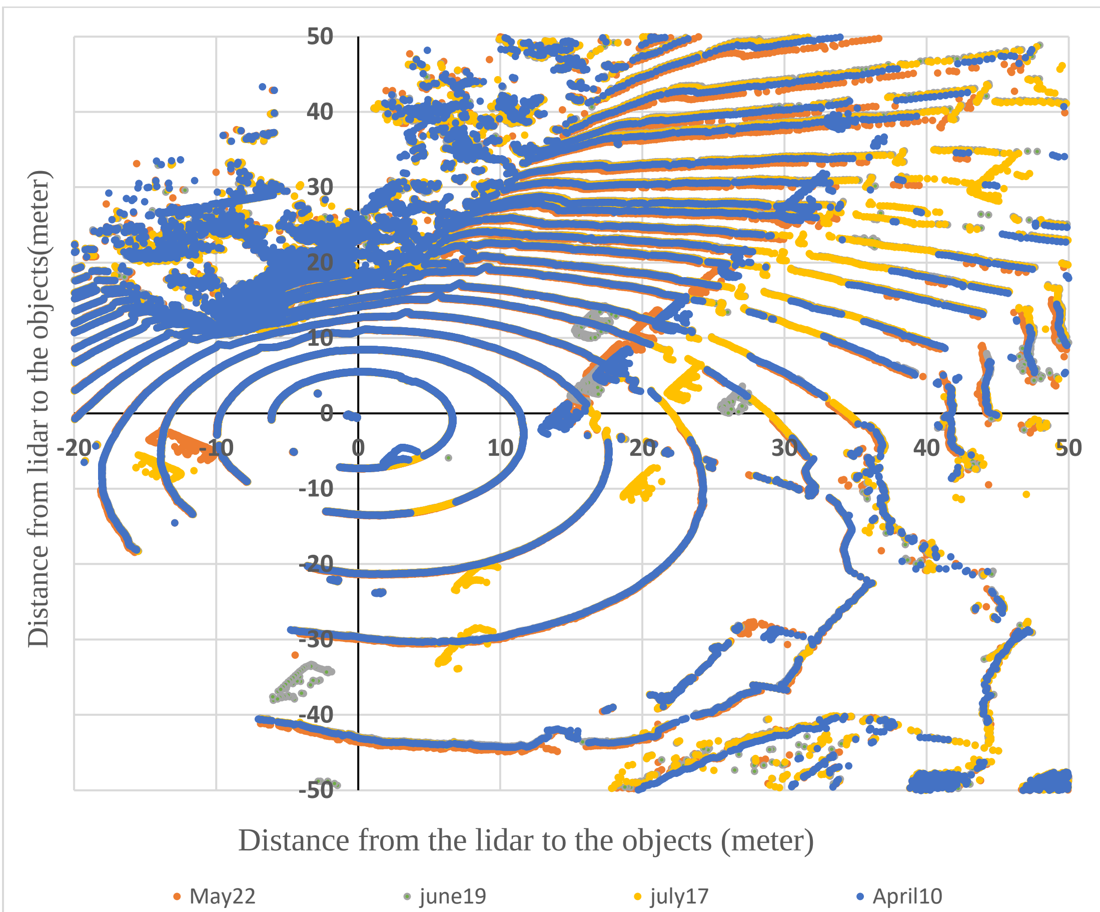


Figure 8: Location of coordinates on same day every month from April-July

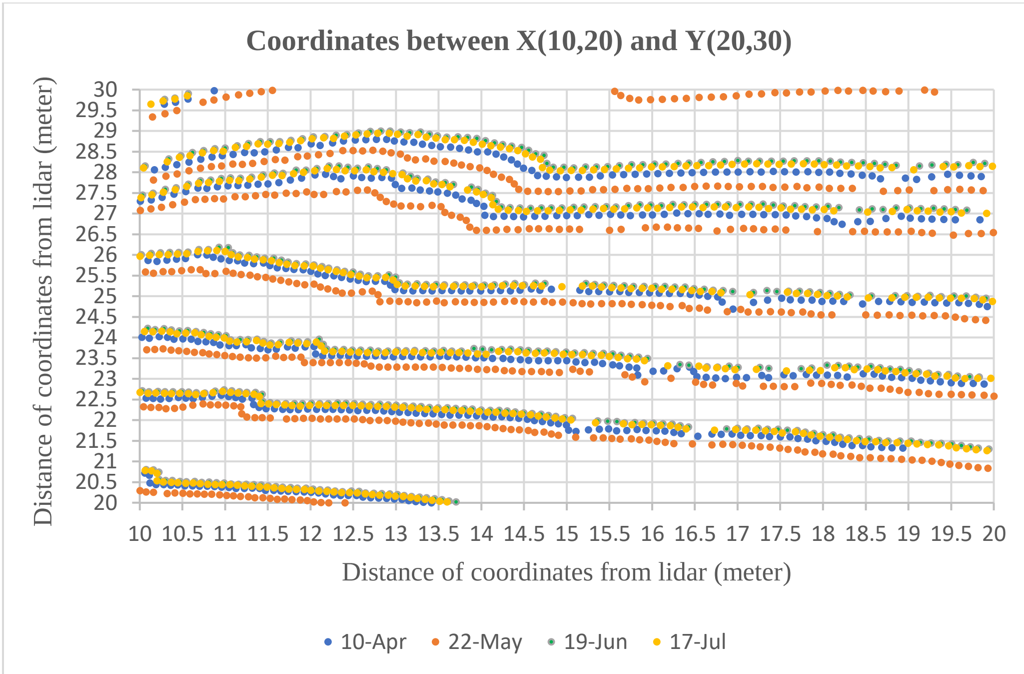


Figure 9: Extension 1 of specific area with offset on same day every month

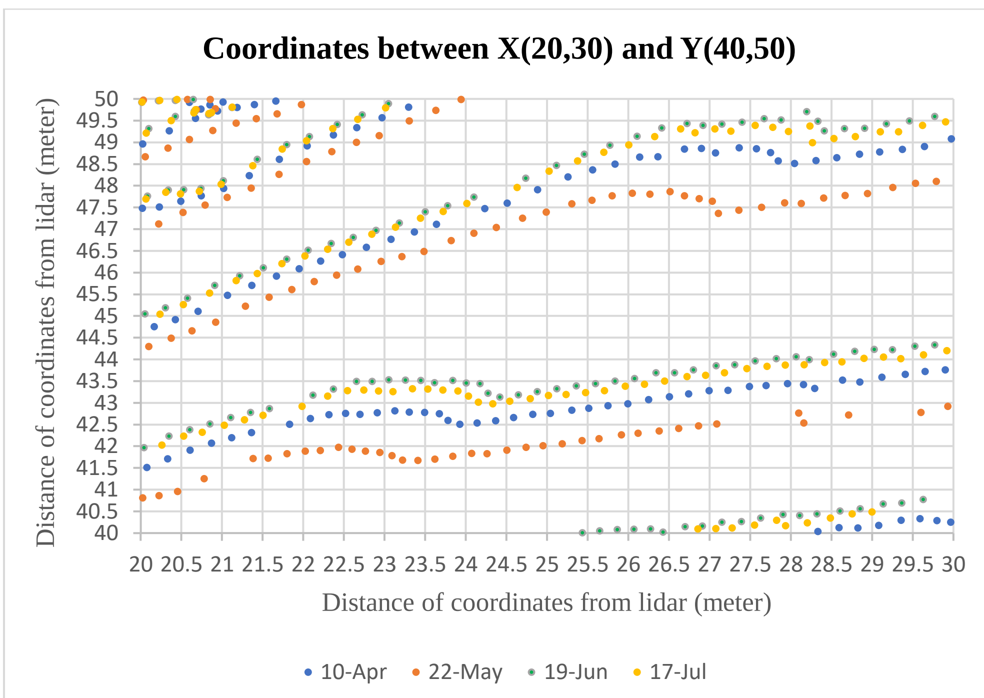


Figure 10: Extension 2 of specific area with offset on same day every month

c) Examining data of same day every week

To see when did the change start, and to find the trend of changes every week 14 Wednesdays in 4 months were considered. By looking at the real-world data, we can see a difference in cloud points from day first to day last. For one cloud point, every week with same Laser beam(id) 1 and same horizontal angle, was checked which is shown through Figure 11.

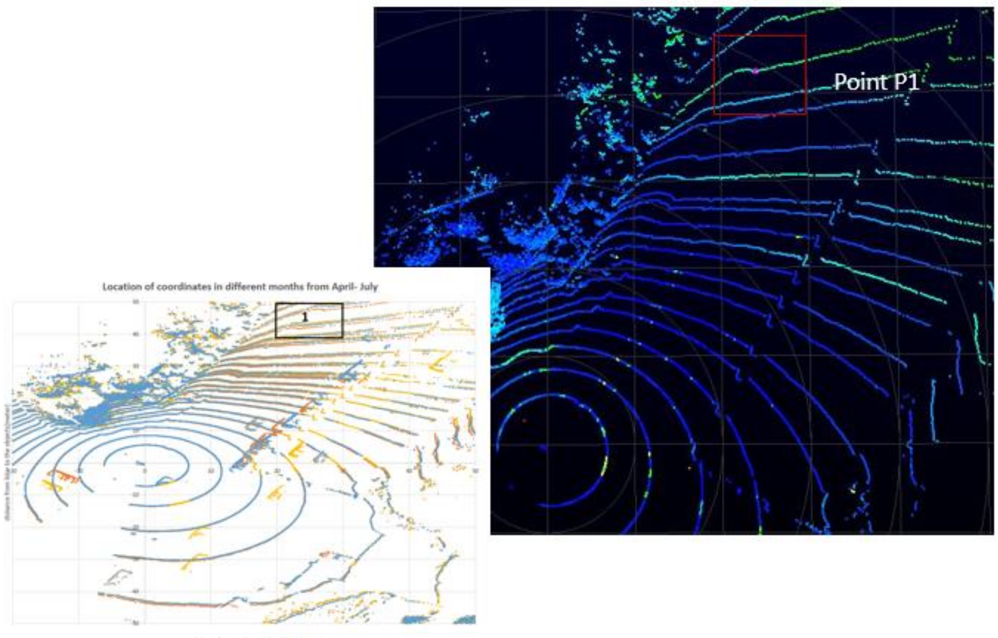


Figure 11: Lidar testing site of McCarran Blvd and Evans Ave

A variation of distance to the point is observed from 48.7- 49.63 m (0.296 to 0.64m), when baseline is considered at 48.99m as shown in Table 1 and accuracy range specified by sensor company is ±3 cm for one frame. So, this clearly demonstrated either environment or surface obstacle had influence on real time data. Therefore, a need of checking some data in well controlled area was required to remove influence of temperature or environment.

Table 1: Measurement of cloud point every week with same laser beam

	Date	Azimuth	Horizontal Angle (degree)	Distance (m)	Drift (m)	Vertical angle	
	10-Apr	3378	33.78	48.996	0	-1	
	17-Apr	3361	33.61	48.7	-0.296	-1	
	24-Apr	3363	33.63	49.04	0.044	-1	
	1-May	3376	33.76	49.16	0.46	-1	
	22-May	3363	33.63	47.86	-1.18	-1	
	29-May	3382	33.82	49.41	0.25	-1	
	5-Jun	3373	33.73	49.39	1.53	-1	
	12-Jun	3372	33.72	48.26	-1.15	-1	
	19-Jun	3377	33.77	49.63	0.24	-1	
	3-Jul	3388	33.88	49.49	1.23	-1	
	10-Jul	3383	33.83	49.54	-0.09	-1	
	17-Jul	3373	33.73	49.43	-0.06	-1	
	24-Jul	3380	33.8	49.52	-0.02	-1	
Laser id 1	31-Jul	3388	33.88	49.62	0.19	-1	Time 7 am

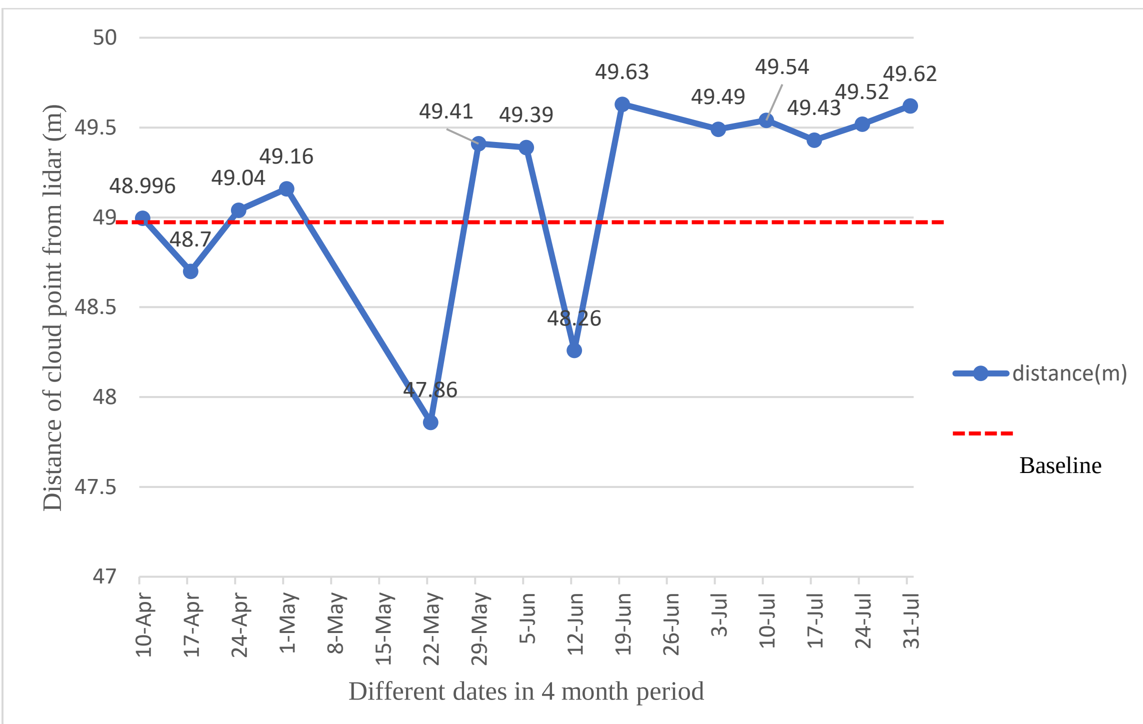


Figure 12: Change in cloud point in 4-month period

4.2 Experiment No.2

4.2.1 Introduction

Considering the diversity of sensors and surface obstacles, the outside environment was simulated to test Lidar in varied scenarios. The focus of this experiment was to create a method to detect surface obstacles, which could later be reciprocated in outside environment and validated through real time traffic data. The current methods of conducting detection through Lidar could be vastly improved by integrating the surface obstacle issue.

4.2.2 Apparatus Setup

The laboratory experiment was conducted using the 360 ° rotating Lidar (Velodyne) with sixteen laser beams (VLP-16) in a well-controlled environment, without any environmental influence. This sensor being smaller in size and lesser in price, could be used for simulation, than compared to the 32 channel Lidar which is used for traffic data collection normally. WETLAB, the area in which the procedure was carried out, was approximately (10’ X 15’) i.e. an area of 150 sq. ft. Since the temperature inside was controlled, the next step was to select the correct resources for experimental simulation, with surface characteristics that would be commonly found in atmosphere. Target materials that were basically used were dust, water, and hydrocarbon.

Aggregate powder was used for dust and was obtained from Pavement Engineering laboratory. Although the particles in air are considerably fine grained, the practical scenario hard-pressed toward using <=75 micron passing sieve which was physically present in lab. Hydrocarbon whereas was obtained from the half-burnt asphalt to simulate the Particulate

Matter triggered from ignition of motor vehicles and wildfires in urban atmosphere. Tap water was used for the procedure.

For instrumentation setup, the laser scanner was mounted vertically above the level tripod being 1.5 m from the wall. The scanner was held static throughout the experiment at the edge of a metal table. Standard RSC corrugated boxes of size 3' X 3' were used to cover the tripod, with voids on 5 sides to introduce the sensor exterior surface with different surface obstacles. A dryer and diffuser was used to simulate the air flow with a constant vessel speed, whereas mechanical characteristics of rain waters was simulated by a lightweight and portable handheld pump sprayer with adjustable nozzle for adjusting the intensity of water from direct injection to fine spray. The setup and process are demonstrated through Figure 13.

The procedure was thus aligned in few steps.

- Dust was diffused through the cavities with the help of blower, to simulate the dust collected through dry weather. The box was thus removed, and data was collected for 10 minutes with a camera on a tripod nearby processing the video recording.
- Next, the sand dust was mixed with water in the portable pump and was sprayed with a consistency, to simulate the debris or dirt collected in the start of the rainy season. The droplets were seen in the form of stains.
- Simultaneously, in the third scenario, the obstacles collected through wind or at the end of rainy season was simulated with the spraying of water on the lidar glass house followed by the blowing of dust.

- Similarly, sand dust was mixed with burned asphalt breezed on the glass house.
- The next situation, housed spraying of a mixture of sand dust, water, and hydrocarbon.

The data was then clipped of 10 minutes for each scenario.

Figure 13: Experimental Simulation

4.2.3 Data Processing

For this experimental plan, even though the data was collected for 10 minutes, only 1-minute data was analyzed for different scenario to determine a method for further real time data. Data from the VLP-16, measurements were investigated using the sensor's inherent visualization software, Veloview, in the format, pcap, and exported to .csv. The data processing was executed with some manual processing through Excel and finally through the software PYTHON for comparing substantial no. of laser beams (ids) and frames to incorporate and justify data of a longer period. At the beginning, the data was manually cleaned to remove flyers. This laser generates relatively clean point clouds and needed very little cleaning. In the instrument, specific angles and their positioning are identified, zero degree being in the opposite of the main wire and the angles till 360 degree moves in a clockwise direction.

For the preprocessing of data, four scenarios were tested with arrest period of 5 minutes between each for the apparatus setup for preceding scenario.

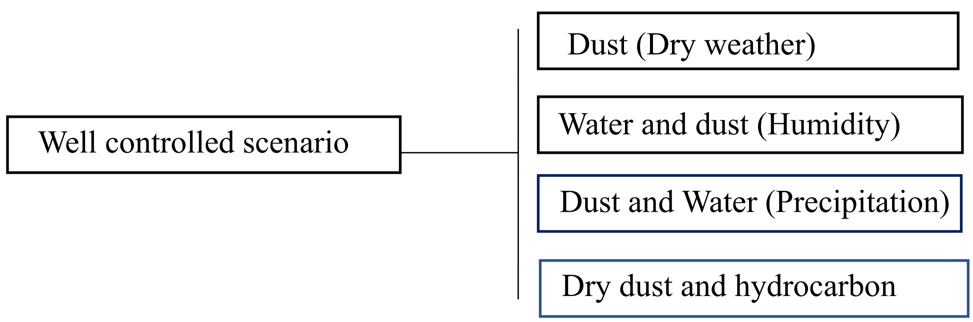


Figure 14: Different simulated scenarios comparison with well controlled scenarios

The postprocessing steps were undertaken for all the recorded data: Real time frame data was obtained from Lidar and was compared with a standard frame. The standard frame is a base frame, in this case, it was the one which was taken from a well-controlled environment and a clean surface/setup without any hindrance or any obstacle. This reference frame was randomly selected, to avoid bias and compared with other frames of simulated scenarios of 1-minute data (600 frames). Frame offset was thus obtained.

Sensor itself may have many cavities; therefore, the limiting range which would accommodate the real traffic needed to be determined. When we have sensor on roads there will a flow of vehicles, start and stop for different location. A threshold therefore for each angle was determined according to pattern of offset in all beams for different angles. Frame offset obtained is thus compared to this limiting or threshold value. Since there is no true value to compare the measured value, the accuracy is not determined rather the reliability of the sensor is obtained. The over threshold offset time is finally calculated and thus is used to notify for the maintenance to the engineers.

4.2.4 Analysis and Results

A. Comparison of Different Scenario with Standard Frame (Well Controlled)

Amongst different scenarios, two standard frames are first compared with each other, in this case the frames from well controlled are compared with various other frames (600 frames) of well controlled scenario to determine if the cloud point has movement or change in its location from the true value whereas sequentially afterwards, a standard frame of well controlled is compared with frames of dust and water scenario (600 frames). For demonstrating the outcomes, Laser 13 results are used as an archetype. The data collected has various cloud points and all the cloud points has laser id information. The offset in the figure is calculated below based on the angle and laser id.

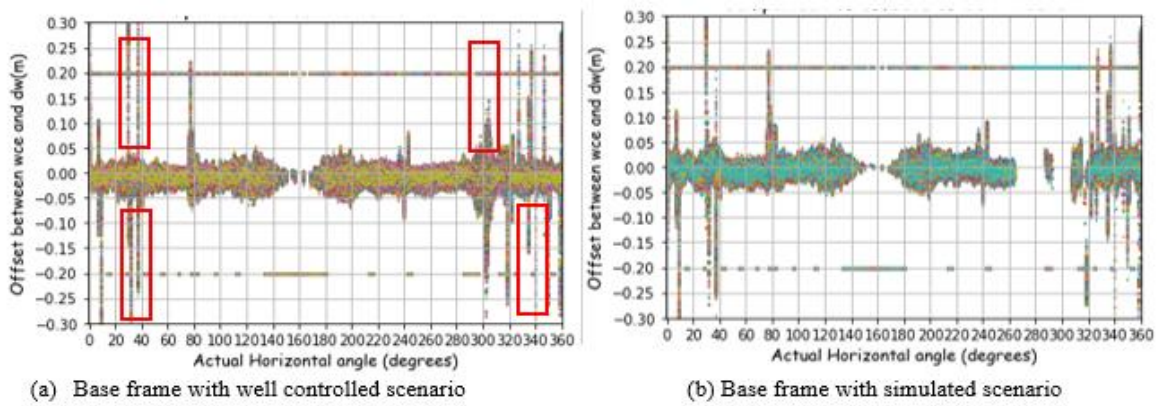


Figure 15: Deviations of points at different horizontal angle for each beam

Test Results

Based on the presented data the following observations can be made:

Fig 15 (a) shows, even with a clean surface and well controlled environment, the cloud points are very scattered and skewed and can be different for different angles, some of the laser light being fore scattered at large incident angles. In the red box on the left and right, distinctly, the cloud points at some angles are at peak, i.e. more than average offset on specific angles (20º, 40º, 80º, 300º, 320º). Therefore, nothing can be 100% accurate, even clean sensor itself make some noise. Effect is noticeable even for smoothest surface, detecting malfunction even before installation. Hence irrespective of the installation of the sensor this method can tell a fault in the Lidar by showing offset at different angles even in well controlled environment.

In addition to this, it shows loss in cloud points in between 140º-170º. The lost data problem, although is not a sensor problem but is caused because of Lidar's proximity with the wall of 0.5m. To validate this, the technical specifications of the sensor was checked which illustrated the minimum distance for measurement is 2m, i.e. below this range the data points could be lost. A substantial input was also obtained from this experiment, sidestepping its specification was, Lidar can read data even at minimum of 0.5 meter.

Comparing the well-controlled scenario with simulated dust and water scenario, fig 15 (b) illustrates additional irregular or abnormal distribution of points showing surface obstacle influence on Lidar. Due to surface obstacles like dust, water droplets, the laser beam is scattered and thus causing degradation to the input signal. Due to droplets or spots on surface of glass house the offset distance increased significantly from, on average, 0.025 m to 0.2 m.

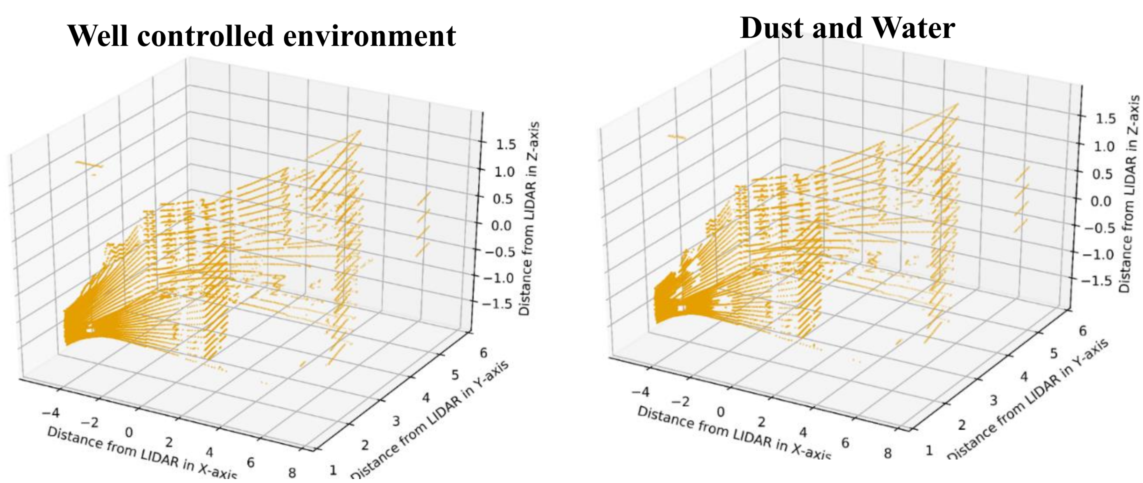


Figure 16: Surface obstacle influence on all laser beams in different scenarios

In figure 15 (b), when well controlled scenario is compared with dust and water scenario, at different angles, the cloud points are additionally erratic and show more skewed distribution (10º, 20º, 60º, 320º, 360º) with an increase in the lost points in compared to well controlled scenario (140º-170º, 260º-310º). The average value of offset ranges from -0.025m to +0.025m and, remains constant during the experiment with maximum no. of frames, at all angles.

With only one scenario and laser beam comparison the results could not be justified. Therefore, different laser beams results were compared for same scenario and similarly different scenario comparison for same beams were executed.

Influence of stain on varied laser beam

The influence of the surface obstacles (dirt or water) was unlike on different laser beams. Offset was in a patterned manner with the low range. The lowest most laser beam have the least effect in every scenario since the lowest beam has the shortest measure distance whereas the one that has the longest distance from the object had much more influence. Through figure 18, it represented, the farther away the object is from the laser, the additional the data quality is influenced.

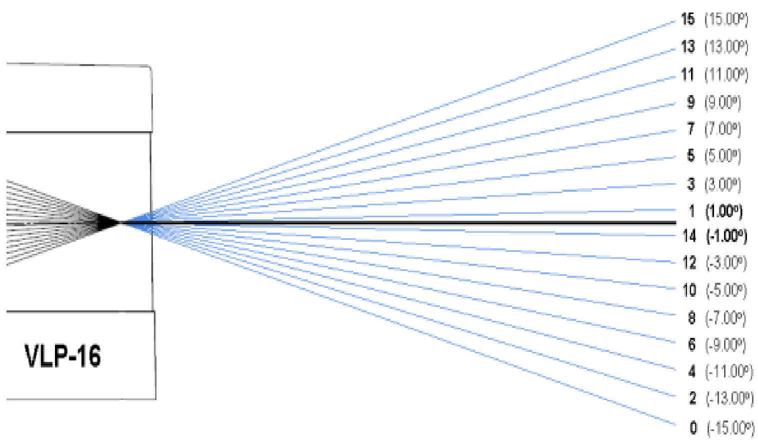
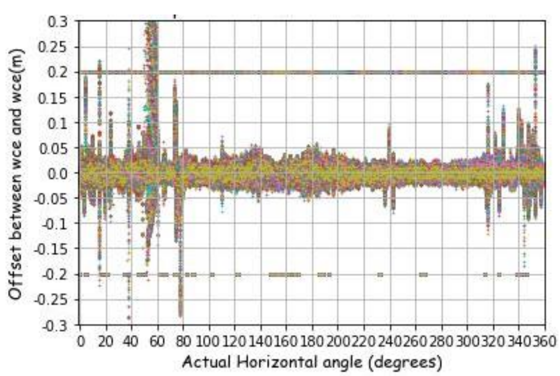
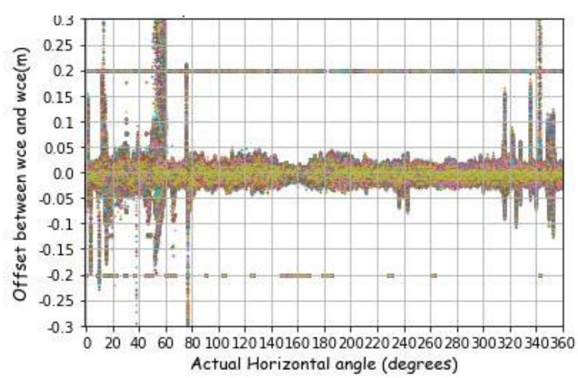


Figure 17: Alignment of beams in VLP-16

ID 0



ID 2



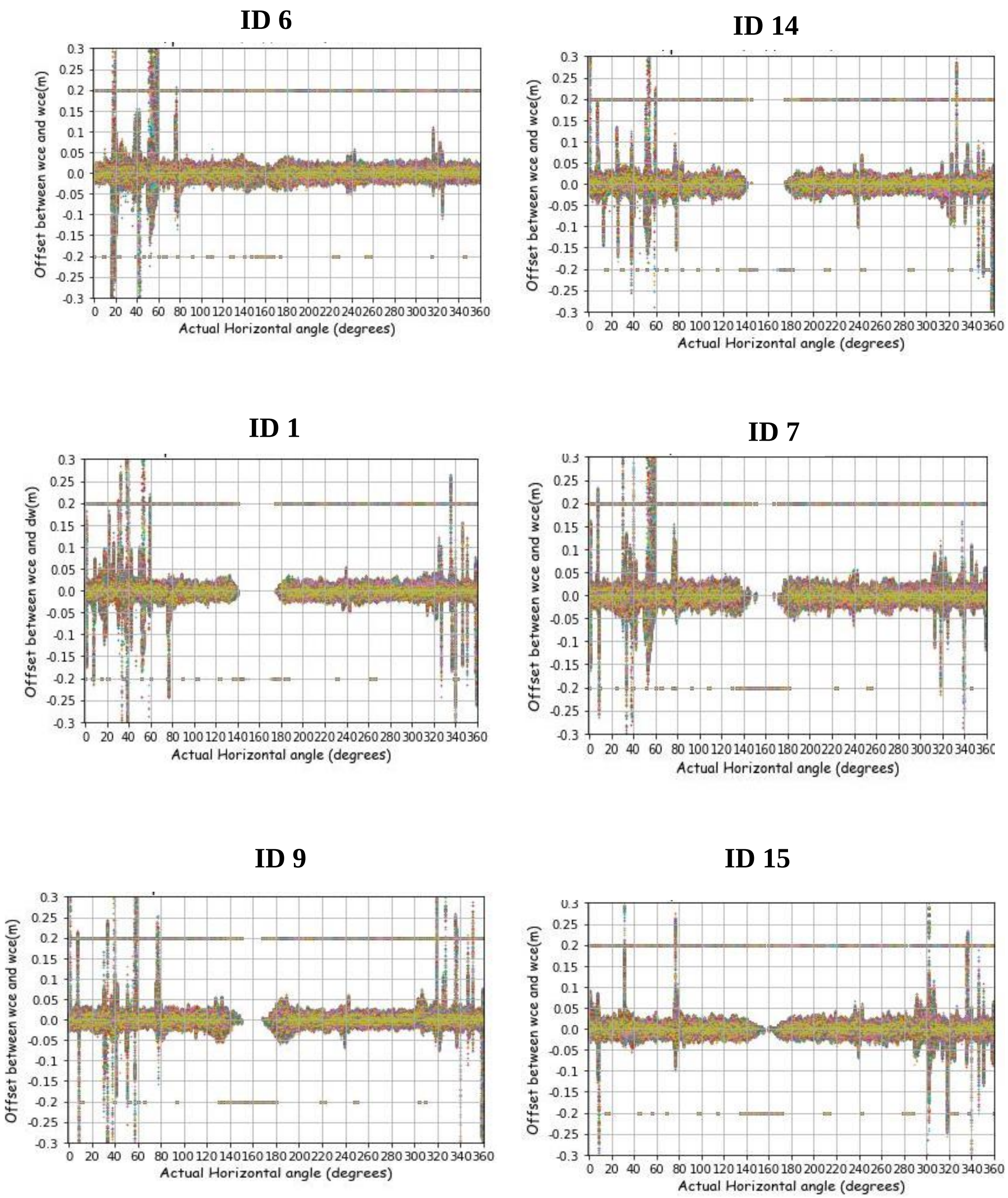


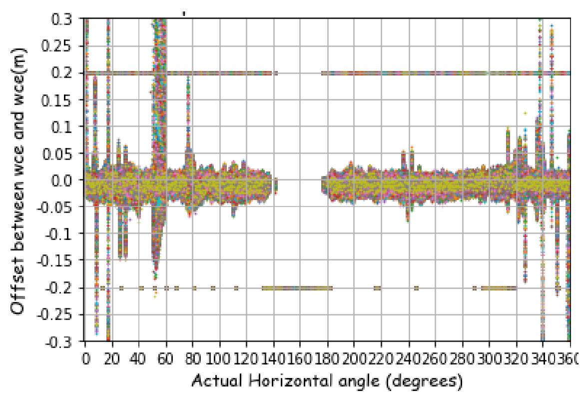
Figure 18: Varied influence on beams compared to standard frame in same scenario

Influence of stain on varied scenario

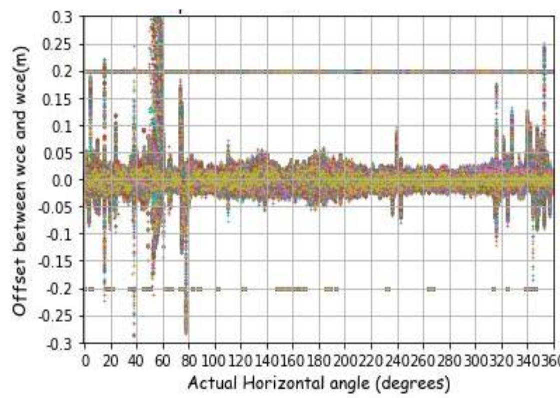
To validate, different scenarios were tested after trying different laser beams from same scenario. Scenarios with well controlled, dust and water, sand and hydrocarbon and water dust comparison were executed with standard frame and the results had no change. Loss of data points with abnormal distribution and additional offset range, in simulated scenario was analyzed with lowest beam being least influenced.

a) **Standard frame/Well controlled scenario**

ID 12

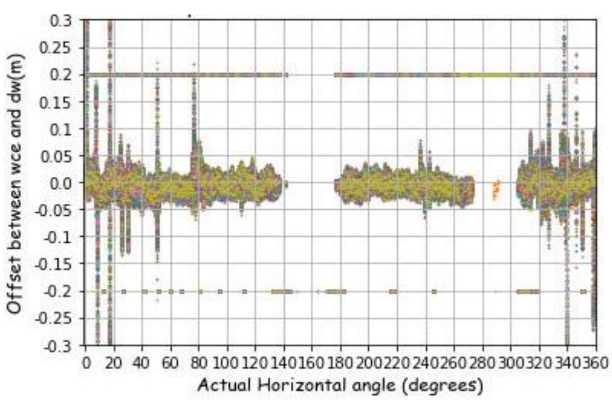


ID 0

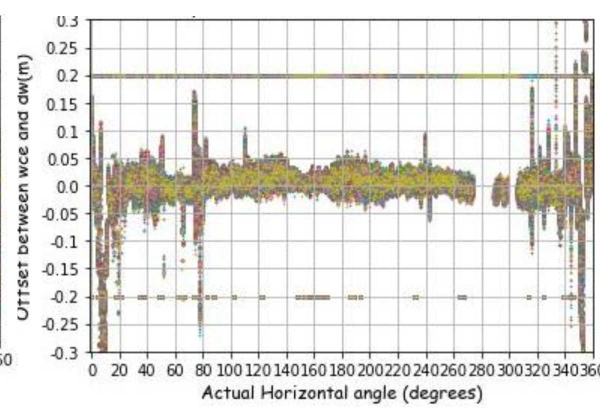


b) **Standard frame/ Dust and water scenario**

ID 12

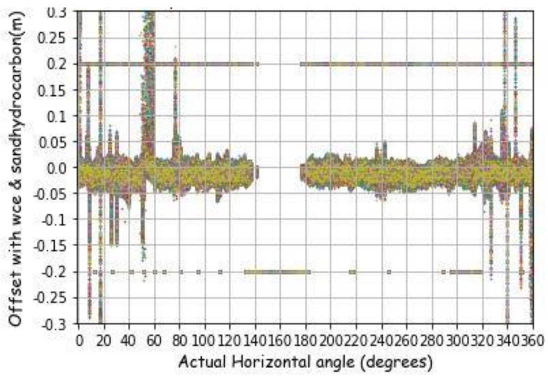


ID 0

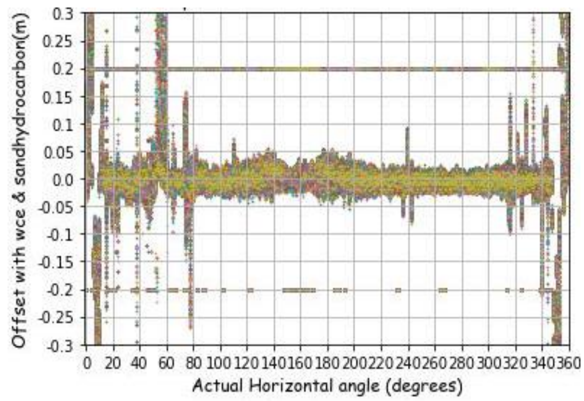


c) **Standard frame / Dust and hydrocarbon**

ID 12

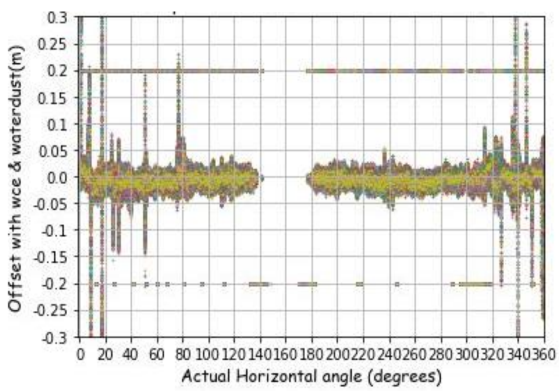


ID 0



d) **Standard frame / Water and dust**

ID 12



ID 0

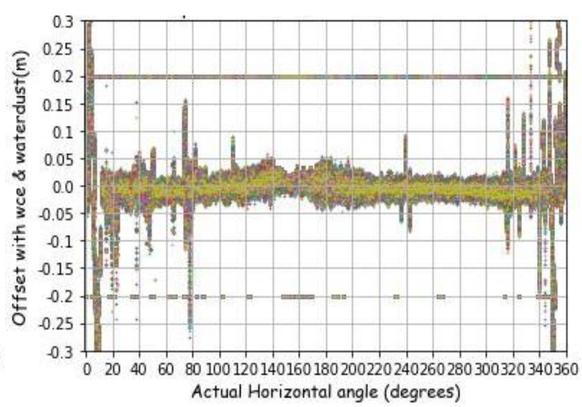
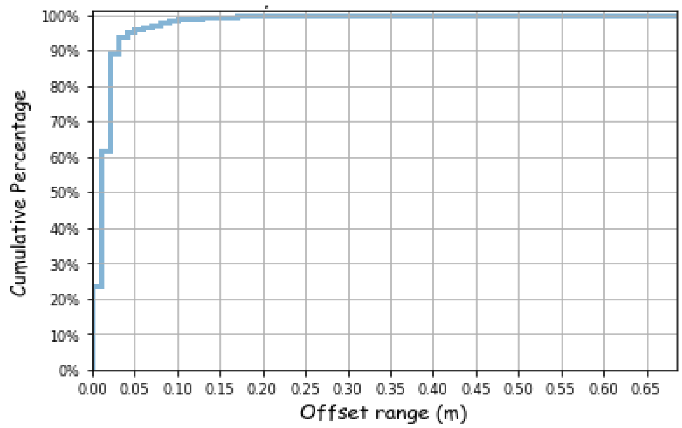


Figure 19: Different scenarios comparison with base frame

After loss of data and skewed points, in different scenarios and same scenarios with varied laser beams it is very clear dust has an influence on data but now the reliability of the sensor becomes a major issue and thus needs to be quantified and checked based on percentage.

B. Reliability of the Sensor

a) Standard frame with well controlled scenario



b) Standard frame with simulated scenario (Dust and water)

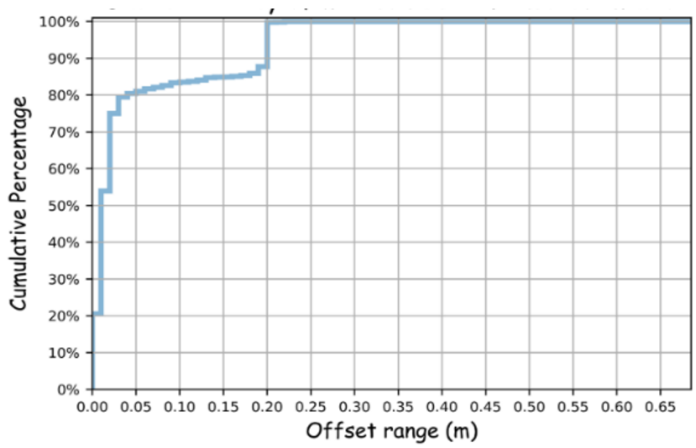


Figure 20: Data reliability in different scenarios with laser id 13

Since drift being seen in well controlled scenario, the reliability of Lidar sensor needed to be determined. In both the figure above, 20 (a) and 20 (b), the X- axis here represents the offset range obtained by comparing frames of same or varied scenarios, which is defined with every 0.05 meter bins and the Y- axis represents the cumulative percentage for reliability of data. Figure 20(a) compares frames from well controlled scenario (600 frames) whereas 17(b) compares a standard frame of well controlled with dust and water scenario (600 frames).

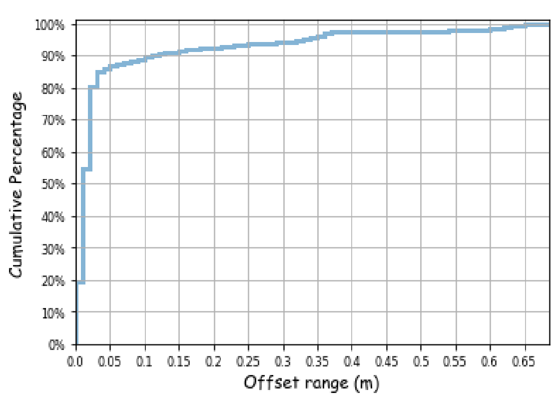
The findings from the analysis were summarized as follows:

Other than noise created by the oversaturation of the sensor by detection of water spots on surface, of the survey vessel, the scanner performed well or seems more reliable for the controlled temperature scenario and performed with lower reliability at large incident angles on simulated scenarios like dust and water. Figure 20(a) illustrates higher reliability making Laser id 13 as a prototype, almost 95 % of the data lies in offset range specified or defined by the manufacturers which is ±3cm for one frame compared to simulated scenario with 80%.

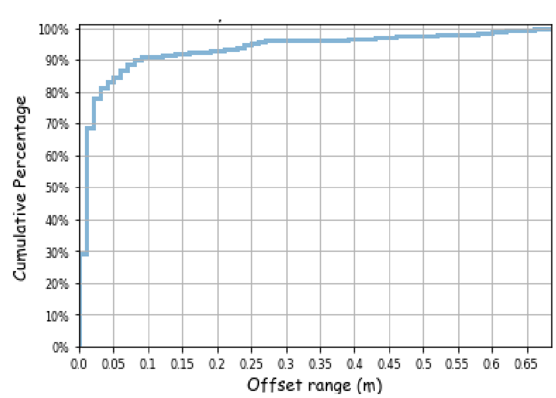
Henceforth, the effect or reliability was checked and compared for different beams with same scenarios. Figure 21 shows, the accuracy level has changed slightly in simulated scenarios from 95 to 90 for laser no.0, 90 to 78 for laser no. 12. The results indicate that even the current laser scanner can detect surficial obstacle with very good accuracy (>=90%) which is highly comparable to the other existing environment perception devices.

a) **Standard frame/Well controlled scenario**

ID 12



ID 0



b) **Standard frame/ Dust and water scenario**

ID 12 **ID 0**

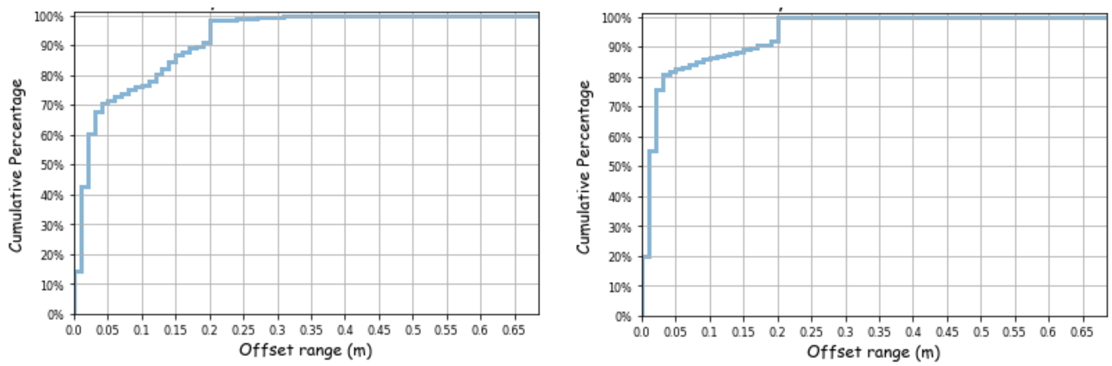


Figure 21: Data reliability from well controlled and simulated (dust and water) scenario of different laser beams

Additionally, when different frames of well controlled scenarios are compared, and accuracy is checked, it clarifies consistency in well controlled frames.

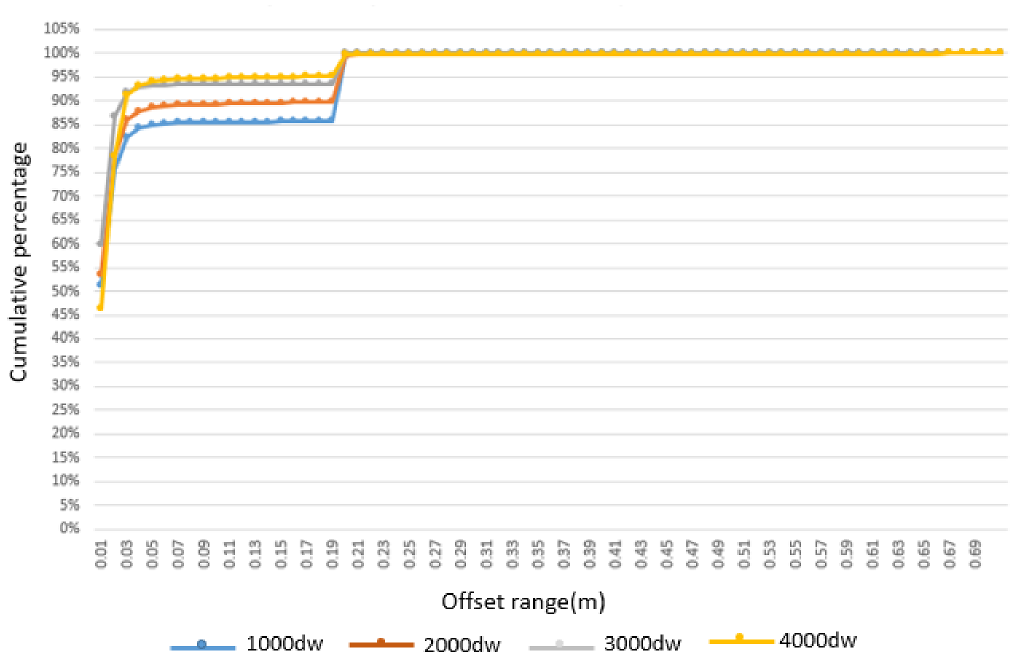
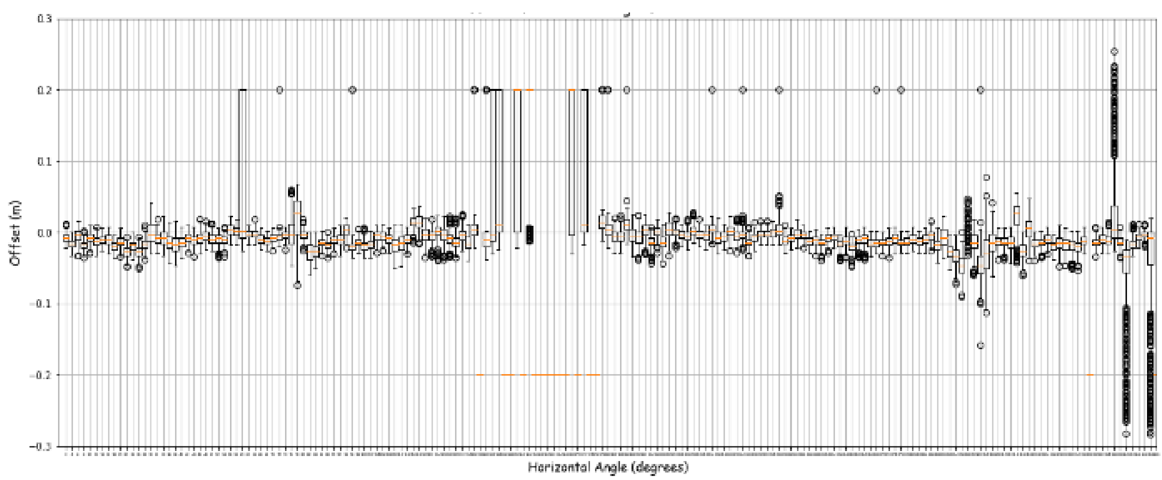


Figure 22: Data Influence of surface obstacle getting minor with time (Laser id 6)

A strong inverse relationship of surficial roughness and time could be seen through Laser no.6; i.e. with time the influence of the obstacle is getting lower. Performance is worst at frame 1000, since the surface obstacle has higher impact but as it increases the reliability seems like well controlled. Thus, figure 22 demonstrate higher reliability of sensor in well controlled environment with the influence of surface obstacle getting minor with time.

C. Automatic Detection of Surface Obstacles

a) Standard frame with Well controlled scenario



b) Standard frame with Dust and water scenario

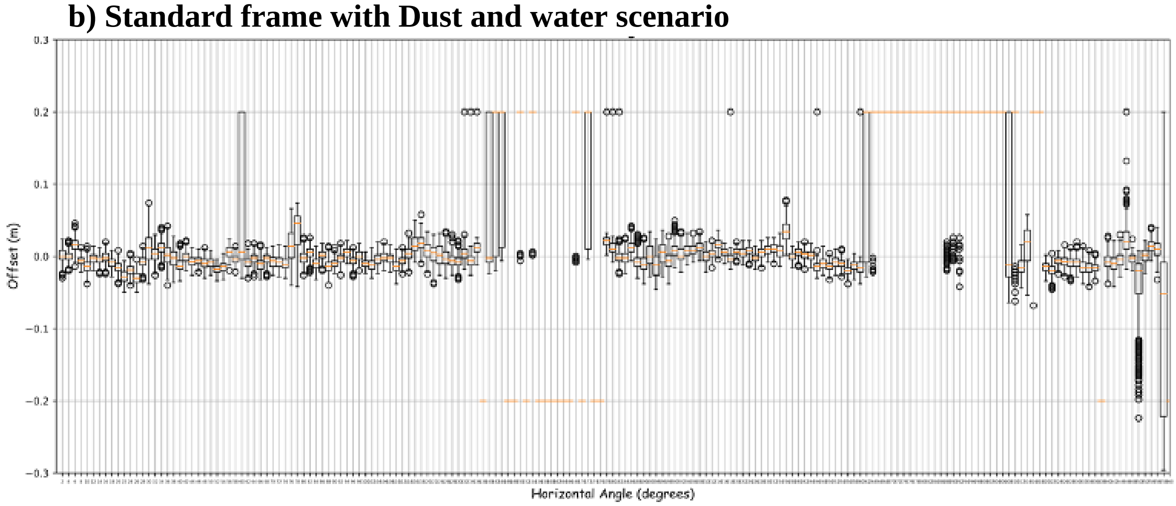


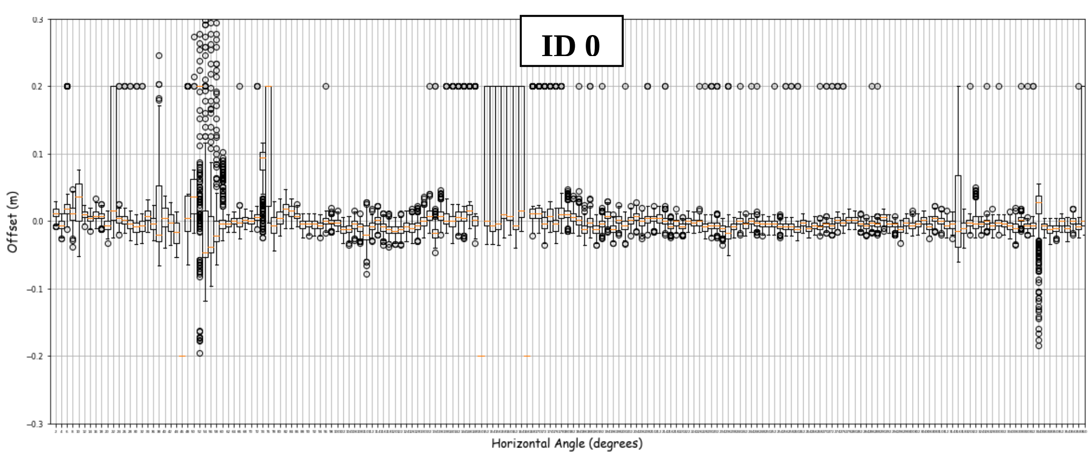
Figure 23: Average, Max, Minim. offset for individual horizontal angles (ID 13)

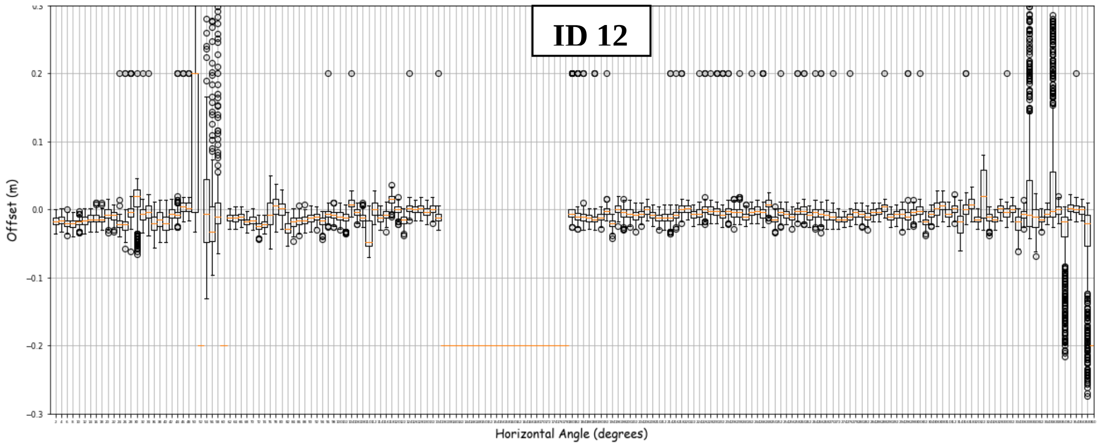
The figure shows the movement of cloud points from their original location in meters in form of offset. X axis represents horizontal angle with bin of every 0.2º, till 360º, a totally of 1800 different angles, and for every angle a Y-value (offset) in meter is present.

The findings from the analysis were summarized as follows:

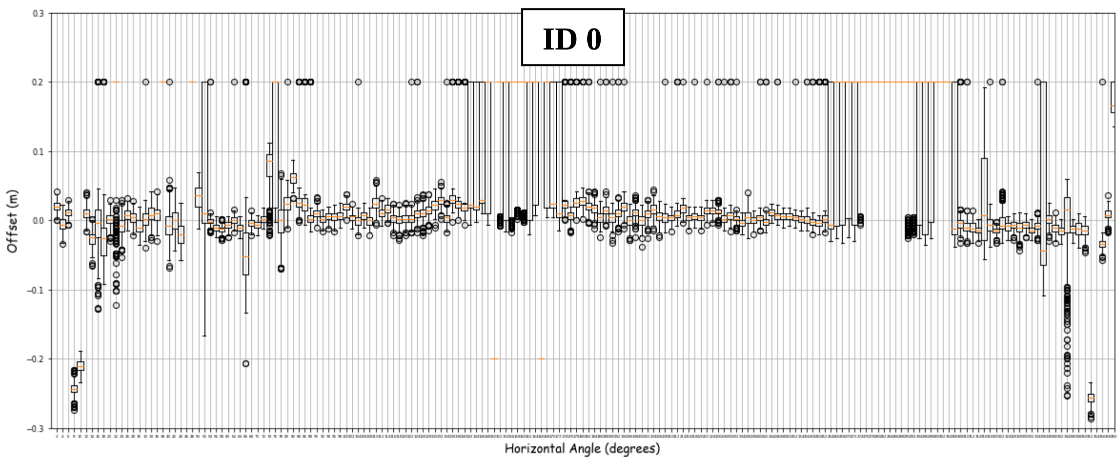
Noise or offset in figure 23 (a) is continuous which is in the in well controlled situation, without any surface obstacle which basically is caused by the sensor itself whereas figure 23 (b) represents, band by band offset in simulated scenario, randomly separated, clearly relating sensor surface with surficial obstacle. It also gives maximum, minimum, average, and different percentile of offset at every angle which helps to determine the limiting range or threshold. From the box plot we can have one value for numerous points. If we see only few angles with larger offset it is normal but if we receive a new sensor with many of the angles having greater offset than defined range, we know there is a reliability issue with the sensor, so we need to replace it or repair it by comparing the frame offset and counting over threshold time period. Similar pattern was observed for almost different beams for same scenarios according to Figure 24.

a) Standard frame with Well controlled scenario





b) Standard frame with Dust and water scenario



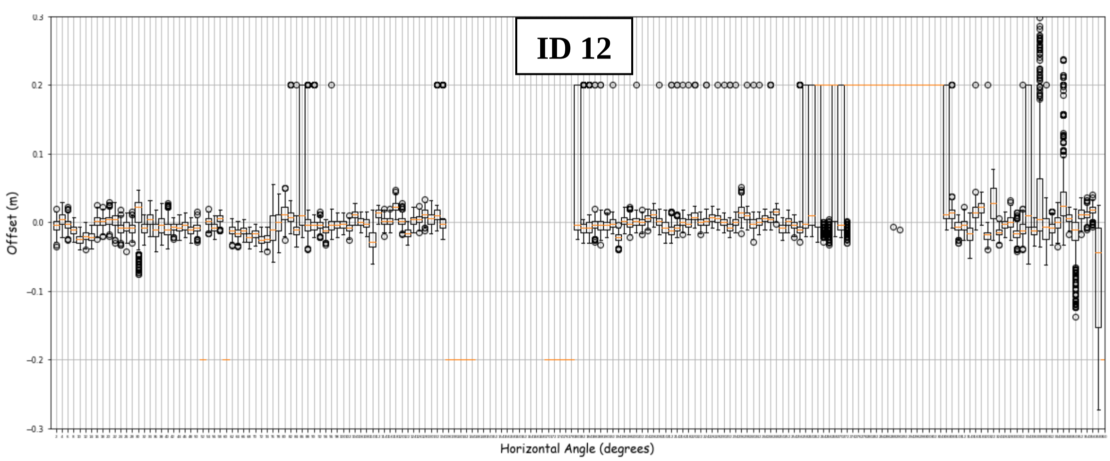


Figure 24: Verification of band by band offset with different beams

Sensor itself may have many cavities; we only need to know the limiting range which would accommodate the real traffic. When we have sensor on roads there will a flow of vehicles, start and stop for different location. A threshold therefore for each angle can be determined according to band by band pattern offset analyzed in all beams.

For threshold we may think different percentile or average offset, as for instance considering 85th highest percentile and 15th lowest percentile, can define the threshold but in all cases it will integrate the cloud points related with the dynamic components or the road user which can result in biasness.

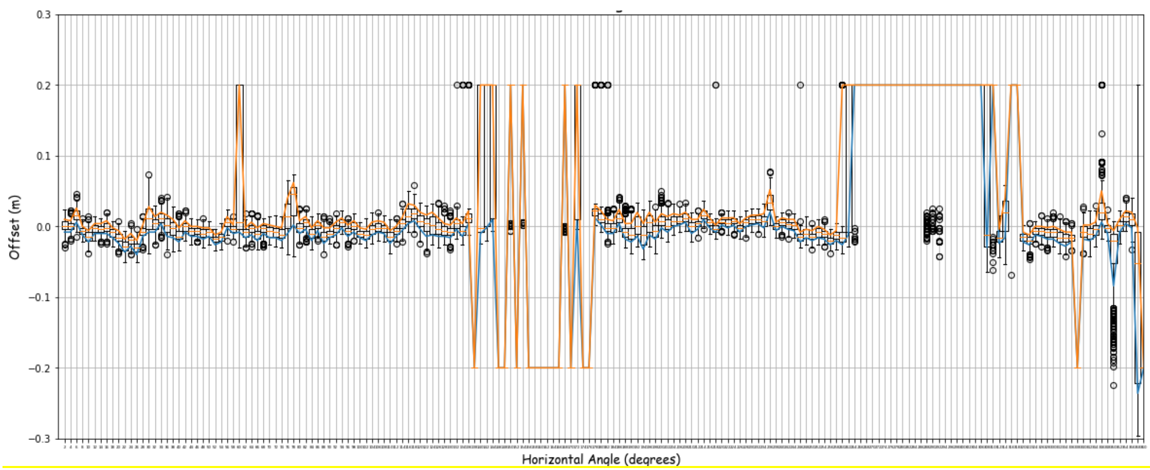


Figure 25: Threshold of offset with 85th highest and 15th lowest with one scenario

Stains being on Lidar surface glasshouse is constant situation and it does not change a long time, so we want to exclude factors or random elements that change along time like traffic or environmental factors. Therefore, if we use median it will exclude, outlier points and negate biasness and for the current situation we will have the normal offset without being influenced by random elements. As such, median value can be triggered for individual angles. The median would be of total number of frames of every angle. This would give 1800 different median points of each angle.

Even the median from each angle is obtained, we still have 1800 angles. For computer program it gets very complicated since the points are not continuous and might be little higher or lower. Additionally, on each angle the surface stain act on different locations of the glass, and therefore each angle is influenced in different levels, so therefore, we want to consider all different influence without excluding any samples. Therefore, to quantify it in an index number, all 360 degree value is converted to one value, including the angular influence at different level.

Therefore, the final change could be automatically detected by getting an average of the 1800 median points of every angle, which would give the threshold value and show whether it’s a major difference or minor difference. This way whether it be with different scenarios or different months or days data, the change due to surface obstacle could be easily found out.

4.3 Experiment No.3

4.3.1 Introduction

To justify the outputs further in the field, with real time traffic data, analysis is executed at the same intersection where it initiated from. A method to determine surface obstacle was determined through the experiment no. 2 in the laboratory but that method need to be validated through real scenarios and situation with the vehicular flow, start, stop and different movements in it.

4.3.2 Apparatus Setup

Lidar (Velodyne) with thirty-two laser beams (VLP-32) was installed at McCarran Boulevard and Evans Ave. This intersection is selected because it is one of the busiest intersections in Reno and has been a priority in traffic safety perspective. Continuous data collection was executed from April 2019 to January 2020, with the Lidar location in the North East side, similar as experiment no.1. More laser beams and frames are used for a concrete conclusion and confirmation of the method developed previously.

4.3.3 Data Processing

The Lidar was setup in month of April and thus is the base or standard data considering no or any influence at that time. Every month data is used, until January 2020 to compare the changes. The data was then clipped of 10 minutes (6000 frames) for each month with either the start or mid of the month. The data used, is of 12 pm (midnight) for all months to negate the influence of traffic. The steps for analysis of data preceded the same as Experiment no. 2.

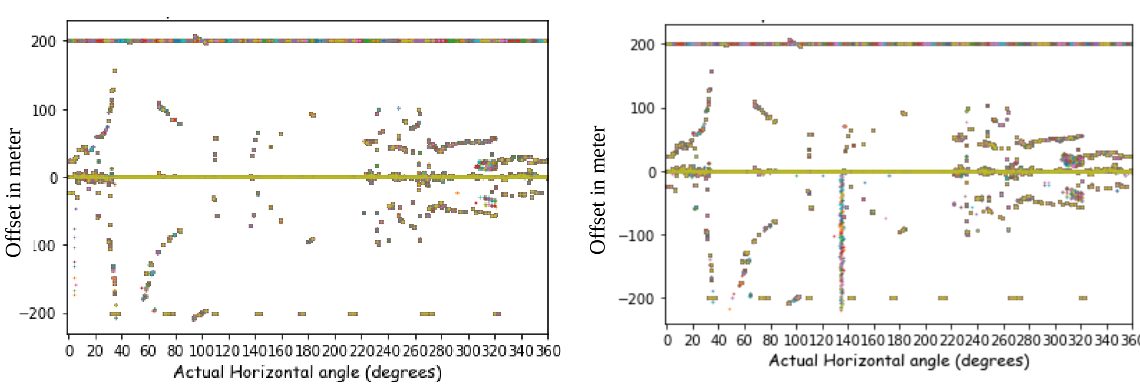
- Every month's data is compared with the standard frame.

- To depict the changes, month by month, taking specific laser ids from 0 to 31, individually median for all 6000 frames for every angle with a bin of 0.2 degree is calculated, with a total of 180 angles. This time automatic programming language is used to get the value.
- Lost points are not considered to assess median and are considered as outliers.
- Finally, an average of all the 1800 points are used to get a threshold value which can be then similarly done for all the months
- The data of individual laser ids are compared for every month which triggers the offset value giving the threshold and the time for maintenance.
- This method helps to measure the difference in cloud point location month by month.

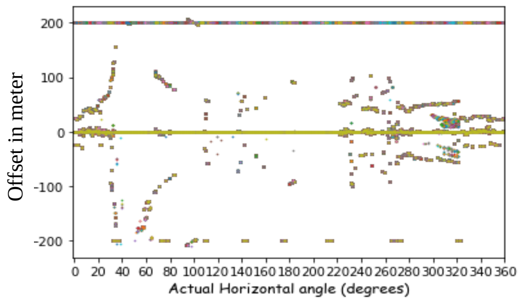
4.3.4 Analysis and Results

A. Comparison of Different Month Data

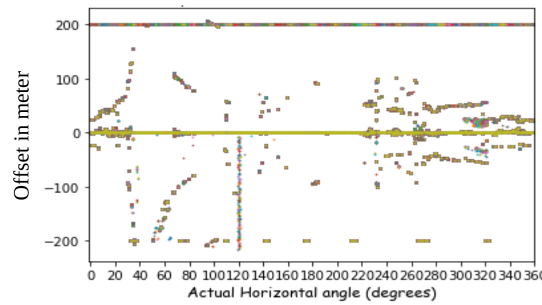
Frame number10 from month of April is used as a base frame and every month half hour data is compared with the same for Laser id 13. The results were as follows:



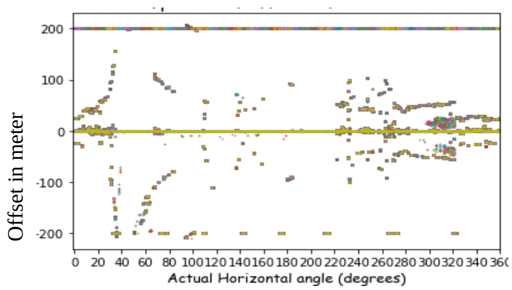
(a) Base frame with 2019-5-1 (b) Base frame with 2019-5-16



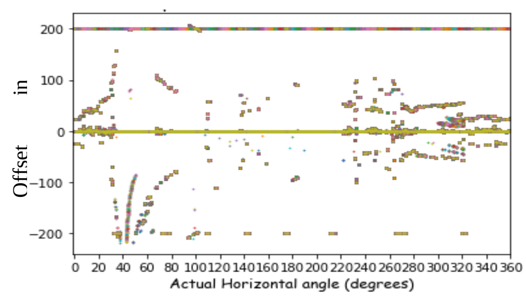
(c) Base frame with 2019-6-1



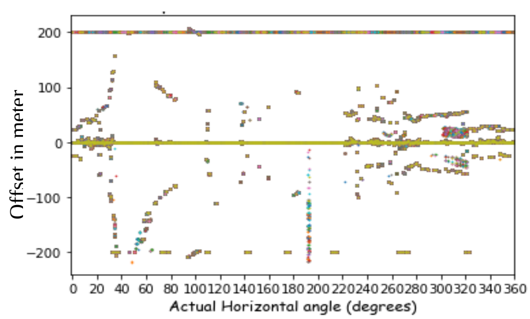
(d) Base frame with 2019-7-1



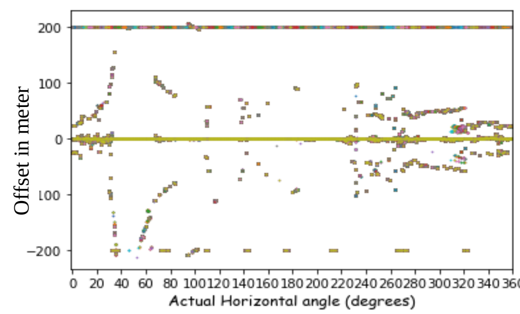
(e) Base frame with 2019-8-1



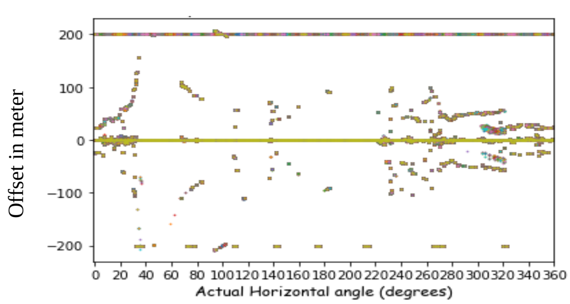
(f) Base frame with 2019-9-1



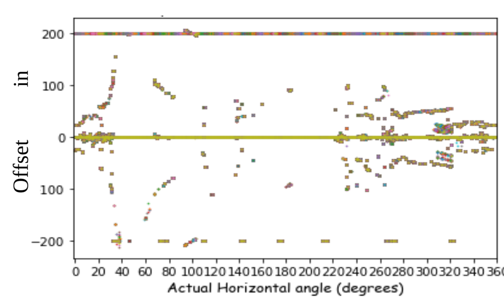
(g) Base frame with 2019-10-2



(h) Base frame with 2019-11-15



(i) Base frame with 2019-12-31



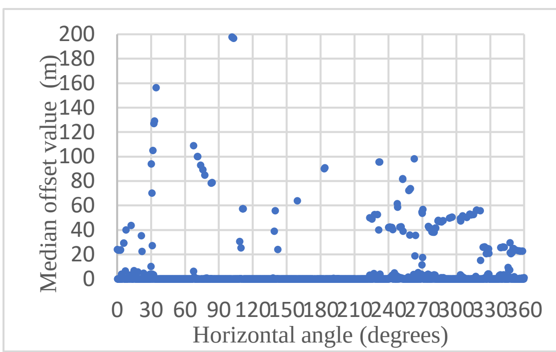
(j) Base frame with 2020-1-12

Figure 26: Scatterplot of deviations for McCarran and Evans (Laser no.13)

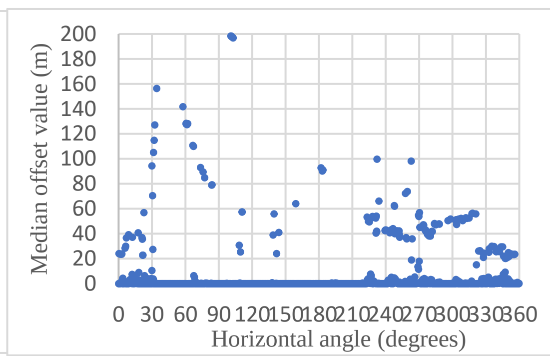
Test Results

Based on the presented data the following observations can be made:

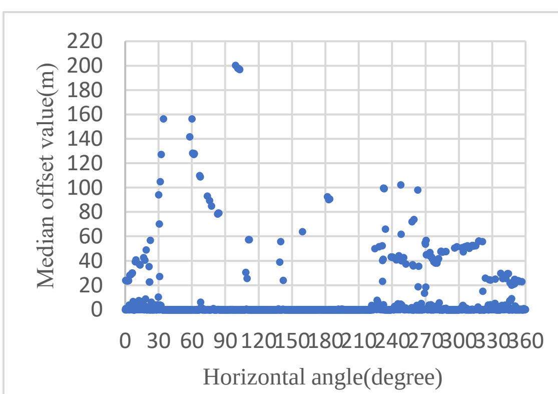
Fig 26 shows, when every month data is compared with baseline data (April's data), the location of cloud points is different for different months and band by band offset is present, which shows influence of dust on surface of Lidar glasshouse. To further quantify this, for every laser beam from 0 to 31, 6000 frames are used, to get median of individual angles for every month data. Since different laser beams (id) behave differently, the specific laser id's median is compared for every month to see the variance.



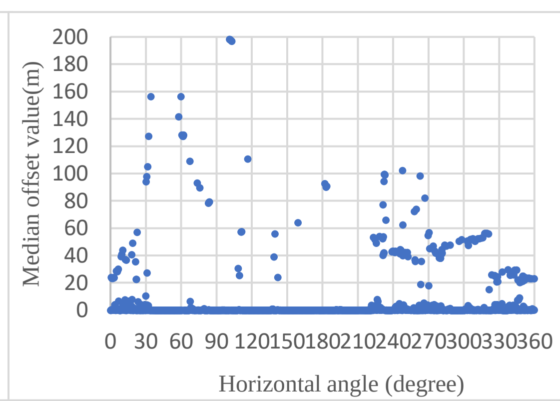
(a) Base frame with 2019-5-1



(b) Base frame with 2019-6-15



(c)Base frame with 2019-7-1



(d) Base frame with 2019-8-1

Figure 27: Scatterplot of deviations for McCarran and Evans (Laser no.13)

As variance is seen, with a single Laser id, and different months data, the average differsum is used to make the real comparison. This value is the average of 1800 medians of different angles for a month. Thus, the results are:

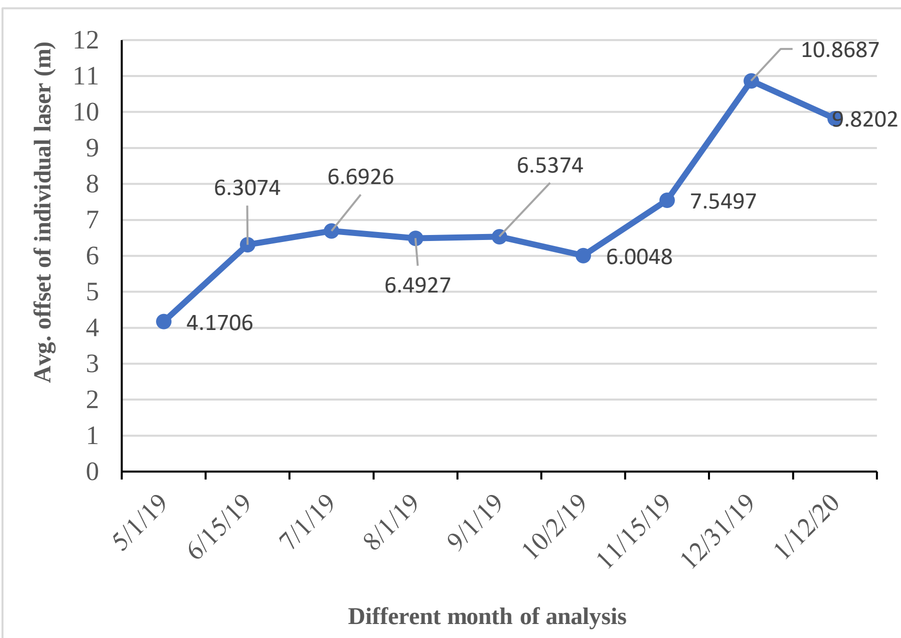
Table 2: Different month of average offset Analysis

Las-er id	**Different month of average offset analysis**								
	2019								**2020**
	5/1	**6/15**	**7/1**	**8/1**	**9/1**	**10/2**	**11/15**	**12/31**	**1/12**
0	0.0749	0.0954	0.1092	0.1066	0.1083	0.114	0.118	0.1037	0.106
1	4.3133	5.2945	5.5083	5.8713	5.7651	5.9498	4.167	4.9955	4.7984
2	3.4185	5.1604	5.0619	5.3473	5.448	5.3345	4.1477	4.0042	4.3589
3	0.1816	0.1752	0.2458	0.2282	0.2466	0.2258	0.268	0.2788	0.274
4	0.1914	0.1707	0.2319	0.2325	0.2505	0.226	0.2732	0.2809	0.2852
5	6.6139	9.393	8.8137	9.3763	9.2428	9.5529	7.1114	8.5264	8.2865
6	5.4162	6.1767	5.8735	6.384	6.0742	6.6256	5.3183	6.3158	6.3744
7	0.6551	0.5971	0.6294	0.5743	0.5818	0.6153	0.6714	0.4811	0.5187
8	0.3177	0.5479	0.6527	0.8531	0.7839	0.7357	0.7624	0.6549	0.5917
9	5.9143	7.7354	8.2588	8.7898	8.9057	9.0751	6.2831	8.6012	8.9349
10	5.3837	7.4388	6.9788	7.8799	7.3507	6.9295	5.6528	7.0372	7.0454
11	1.11	1.4812	1.622	1.6938	1.8822	1.7405	1.6419	1.4382	1.8362
12	3.7402	4.8093	5.5152	5.7559	5.7348	5.1344	5.2021	5.3577	5.6117
13	4.1472	5.8145	5.6127	6.161	6.0214	5.3272	5.2575	5.5545	5.5356
14	5.1491	6.7068	6.8536	7.3522	7.1252	6.8773	6.0614	7.3635	7.7421
15	4.1931	5.4024	6.1161	6.6834	6.1502	5.6651	5.105	7.4109	7.248
16	6.0686	6.4712	7.7475	7.1116	7.1268	7.0363	7.0799	8.0226	8.7104
17	3.6033	4.1548	4.1471	4.7102	4.9254	4.7765	3.6934	3.775	3.7634
18	5.6544	6.8728	6.3698	6.9215	7.0005	7.054	5.714	5.7957	5.8941
19	4.1706	6.3074	6.6926	6.4927	6.5374	6.0048	7.5497	10.869	9.8202
20	4.6555	5.6709	5.0742	5.4939	5.6274	5.1007	4.9017	5.9353	6.1592
21	3.2694	3.6448	3.7121	4.1814	4.0485	3.8352	3.0251	3.1532	3.0006
22	3.1386	4.564	4.9757	5.1751	4.6256	4.6737	3.8735	3.2453	3.047
23	2.4309	4.069	4.1871	4.2522	4.1352	4.0566	3.5812	5.8086	5.2691
24	2.9438	4.1644	4.2305	4.3323	4.8483	4.589	4.3956	5.1903	6.524
25	2.2137	4.2624	3.7862	4.3455	4.191	2.7551	3.2247	2.8366	2.5934
26	3.7642	4.4926	4.7998	5.633	5.309	5.5073	4.354	3.9146	3.8517
27	2.1852	4.0801	4.1384	4.1909	4.3262	3.7122	3.7242	5.3846	5.2899

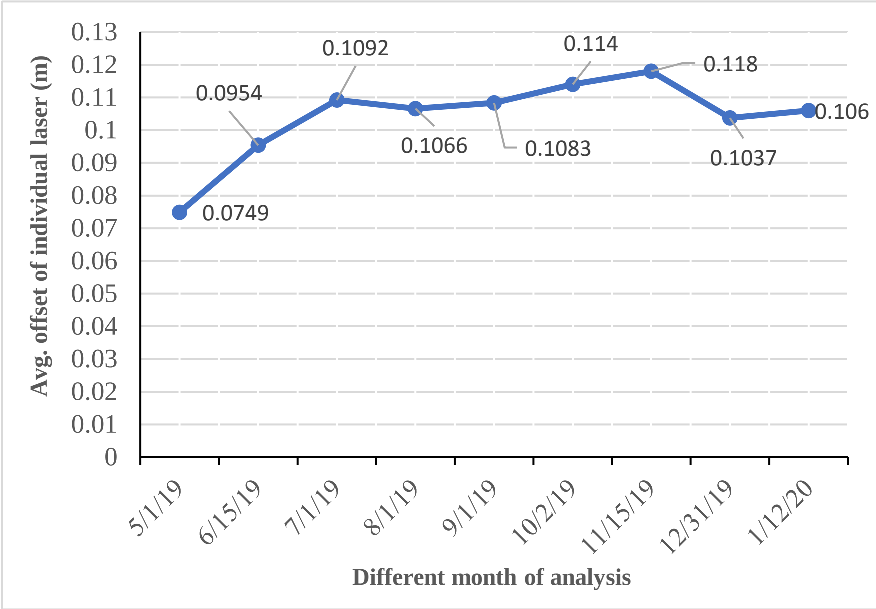
Las-er id	Different month of average offset analysis								
	2019								2020
	5/1	6/15	7/1	8/1	9/1	10/2	11/15	12/31	1/12
28	3.258	4.7628	4.8838	4.8947	4.9555	4.555	3.6765	4.6934	4.6272
29	1.0604	0.9512	0.9367	0.9554	1.1477	1.0421	1.15	1.1185	1.1435
30	3.5509	5.0596	5.3331	5.5659	5.5702	5.0885	4.3497	3.686	3.6393
31	3.1179	5.0408	4.8263	4.9978	5.1787	4.9602	4.0847	7.1261	7.2168
Sum	**105.91**	**141.57**	**143.92**	**152.54**	**151.22**	**144.88**	**126.42**	**148.96**	**150.1**

To find out the trend of offset in every month for individual beam, three charts with maximum difference, with no difference, with minimum difference of offset for individual beams are shown below through Figure 28 and a total month wise difference of distance for all the beams is represented through Figure 29 to depict or identify the threshold.

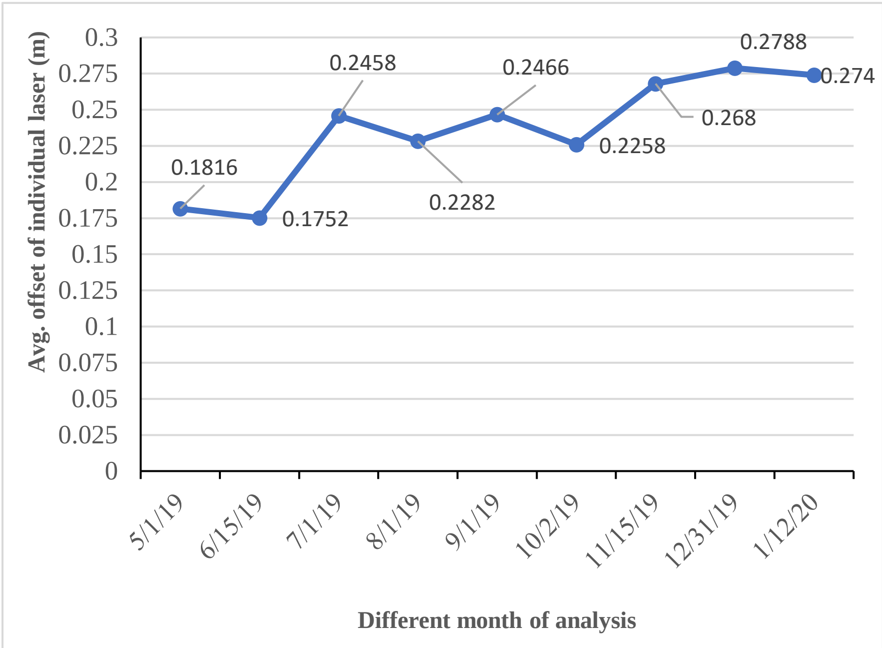
a. With maximum change per month (Laser id 19)



b. With no change per month (Laser id 0)



c. With minimum change per month (Laser id 3)



Laser id 4

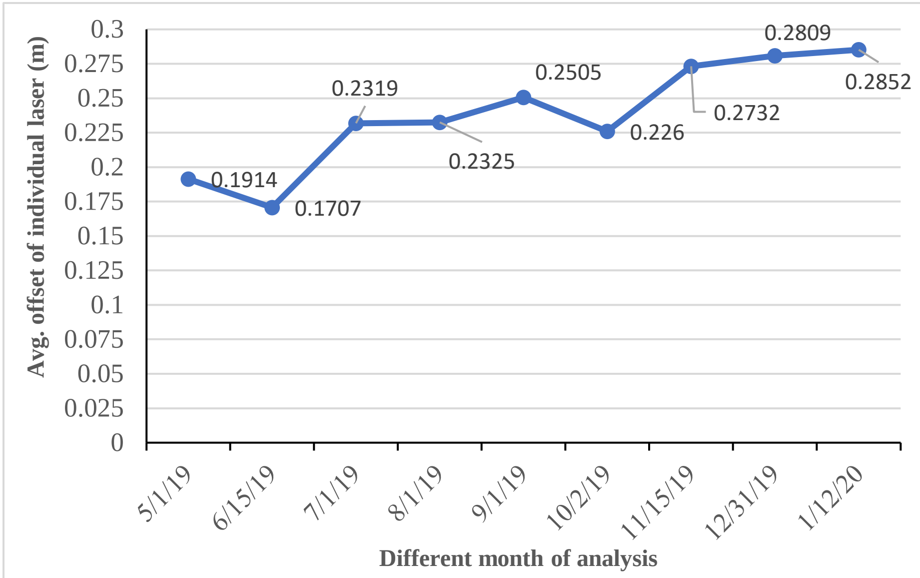


Figure 28: Maximum, minim. and no change in offset per month of individual beams

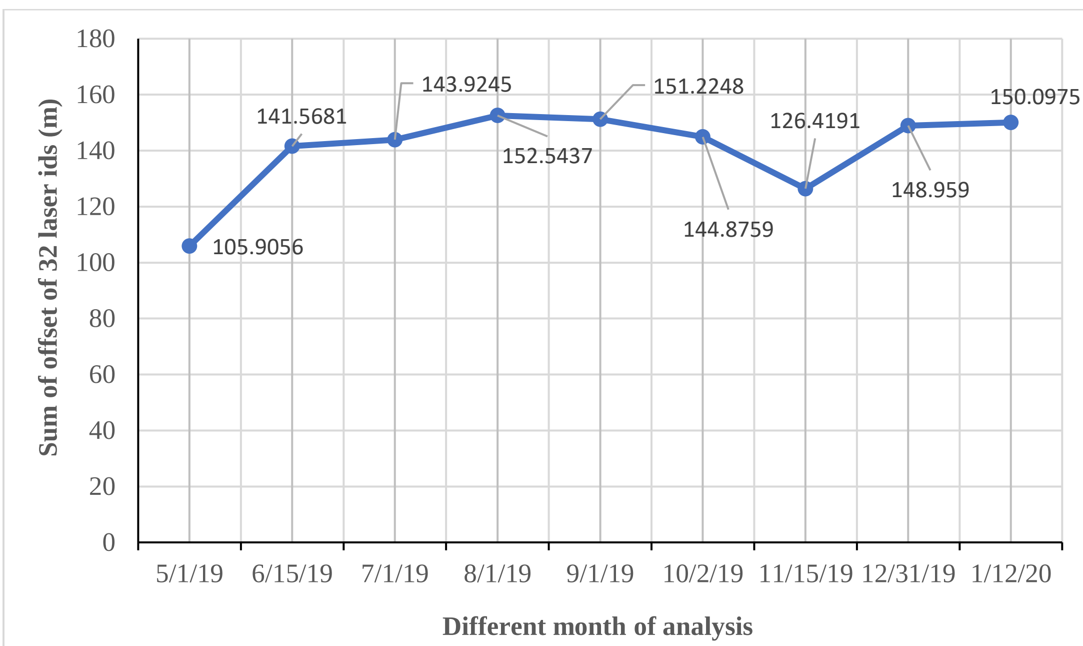


Figure 29: Total change in offset distance every month

All the beams henceforth have different turning points and changes in different month for the offset. Therefore, to find a threshold value, based on chart, observation, and experience of data, according to Figure 28, 141.56 i.e. 142 is considered the threshold value for this specific dataset analysis and scenario. This is based on current scenario and dataset and for future it can be validated with various dataset and scenarios. If the offset distance is beyond that or higher then threshold, then it would trigger the engineer or the related agency to clean or maintain it in this situation.

CHAPTER 5. CONCLUSION AND DISCUSSION

5.1 Inference

Different studies related with sensors have been done, about their pros and cons, the issues related with them but very few studies are related with data quality offered by sensors specially Lidar. Lidar is a new technology and has been used in autonomous vehicles, but the long-term goal is to use it on roadside for traffic safety. Backing this up, the maintenance has not been referenced, as to when it needs to be done to get qualitative data and what should be the frequency. My research therefore gives an automatic method to detect stains or surface obstacle on lidar glass houses and indicates the frequency required to maintain traffic safety, meanwhile saving cost and technical efficiency.

Multiple experiments, comparing different conditions of sensor surface was conducted. The experiment consisted of series of steps where the distribution of cloud points was checked, and offset was calculated by comparison of reference frame with simulated scenario for large no. of laser beams and frames. Reliability was also determined even for the harshest situation. And a threshold range was defined, by getting median from all frames of individual angles and average differsum was used to indicate the limiting value to notify the sensor maintenance requirement. The threshold range was obtained analyzing all beams and provided index value for that situation. The methods developed during experiments was validated with real time traffic scenario.

The specific conclusions that could be made through this study are:

- Previous studies, dialog about how random factors might influence sensors but none of them defined a method to identify the influence of stains on sensor or what should be the frequency to maintain them.
- Since long term goal is to position Lidar on roadside, this study contributes proposing a methodology when the sensor is being influenced and the right time to maintain it
- Regardless of sensor surface being spotless, cloud points at some angles can be erratic.
- Based on some scatter plots, malfunction identification can be performed even before installation of the Lidar through this method
- Harsh outside condition will have abnormal distribution of points with band by band offset, demonstrating influence of stain on Lidar glass house, making reliability dubious
- Although Lidar sensor has frail spots, but their reliability of the sensor is higher even with stains, so it can be used otherwise
- Additionally, this study epitomized how laser beam are influenced differently from stains; the farther away the object is from the laser, the additional the data quality is influenced
- A strong inverse relationship of surficial roughness and time was instituted i.e. the influence of surface obstacle got minor with time
- Sensor itself may have many cavities; we only need to know the limiting range which would accommodate the real traffic. A threshold can be determined according to band by band patterned offset analyzed in all beams for the situation.

- Stains being on Lidar surface glasshouse is constant situation and it does not change along time, so all factors that change along time should be excluded to get influence by stains
- Surface stain act in different levels, so to quantify it in an index number all 360 degrees values can be converted to one limiting value

5.2 Recommendation

Based on literature review and this research the surface obstacle or stains, definitely influence the lidar sensor performance, so, the recommendation through the study is to monitor the lidar sensor data using the high-speed and high-accuracy automated inspection method introduced in this research and the recommended threshold. Nevertheless, when the offset is higher than the recommended threshold that needs to trigger alert or provide a reminder to the technician or engineer to maintain or clean the sensor.

Summing up, any lidar system should use this method to identify how and when the data is being influenced, i.e. both the qualitative and quantitative aspect and provide timely maintenance circumventing serious issue in traffic management and safety.

5.3 Further Study

For future research if someone wants to extend the study, it could include the following areas:

- Further study needs to check the validating detection range for each laser beam, more cases, more data, and sites

  - The threshold value needs to be validated and checked with furthermore scenarios, site and dataset.
  - When its rainy data, how it influences the performance could be checked further. In a small room significant influence was not observed through this study. It might result differently with a real time traffic data which could be studied further
- With technological advancements, surfaces are getting complex to be examined through human vision. By contrast, it remains difficult for a computer too because of various defects such as scratches, cracks, stains, scars. When several types of defects exist in an inspection region, the further approach could be to treat each type of defect separately.
- The conventional method directly inspects defects in a region without considering texture which affects the accuracy of inspection and needs to be taken care of through further study.

CHAPTER 6. REFERENCES

[1] IIHS HLDI, 2021. Fatality Facts 2019 Yearly Snapshot. Available at: https://www.iihs.org/topics/fatality-statistics/detail/yearly-snapshot

[2] Scorecard, U.M., 2015. The Texas a & m transportation institute–urban mobility scorecard.

[3] Transportation Statistics Annual Report 1999, BTS99-03. U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, DC. 1999

[4] Davis, S.C. and Diegel, S.W., 2005. Transportation Energy Data Book: Edition 24-2004. Publication ORNL-6973, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[5] Klein, L.A., Mills, M.K. and Gibson, D.R., 2006.Traffic detector handbook: Volume I (No. FHWA-HRT-06-108). Turner-Fairbank Highway Research Center.

[6] Nellore, K. and Hancke, G.P., 2016. A survey on urban traffic management system using wireless sensor networks. Sensors,16(2), p.157.

[7] Hudson, M.(2020). The Intersection of LiDAR, Data and Coronavirus. Available at: https://www.adaptautomotive.com/articles/482-the-intersection-of-lidar-data-and-coronavirus

[8] Klein, L.A., Mills, M.K., Gibson, D. and Klein, L.A., 2006.Traffic detector handbook: Volume II (No. FHWA-HRT-06-139). United States. Federal Highway Administration

[9] Hasirlioglu, S., Riener, A., Huber, W. and Wintersberger, P., 2017, June. Effects of exhaust gases on laser scanner data quality at low ambient temperatures. In 2017 IEEE Intelligent Vehicles Symposium (IV) (pp. 1708-1713). IEEE

[10] McKnight, D. and Miles, R., 2014. Impact of reduced visibility conditions on laser-based DP sensors. Marine Technology Society: Washington, DC, USA.

[11] Barbagli, B., Manes, G., Facchini, R. and Manes, A., 2012, June. Acoustic sensor network for vehicle traffic monitoring. In Proceedings of the 1st International Conference on Advances in Vehicular Systems, Technologies, and Applications (pp. 24-29).

[12] Guerrero-Ibáñez, J., Zeadally, S. and Contreras-Castillo, J., 2018. Sensor technologies for intelligent transportation systems. Sensors, 18(4), p.1212.

[13] Types of autonomous vehicle sensors in self driving cars (https://www.itransition.com/blog/autonomous-vehicle-sensors

[14] How LiDAR is changing the world: Construction and city planning to the Amazon and Notre Dame, By Charles Thomson

[15] Topcon Positioning. (2020). Using Mobile Lidar for Highway Road Maintenance. Available at: https://geo-matching.com/content/using-mobile-lidar-for-highway-road-maintenance

[16] Campbell, B, A. (2020) Sensor Cleaning Tech: How Engineers Protect Sensors from Bugs, Bird droppings, Dirt & Grime. Available at: https://www.autovision-news.com/sensing/sensor-technology/sensor-cleaning/.

[17] Yu, X. and Marinov, M., 2020. A study on recent developments and issues with obstacle detection systems for automated vehicles. *Sustainability*, *12*(8), p.328

[18] Wang, K. and Liu, Y., 2014. Can Beijing fight with haze? Lessons can be learned from London and Los Angeles. Natural hazards, 72(2), pp.1265-1274.

[19] Zhang, D., Liu, J. and Li, B., 2014. Tackling air pollution in China—What do we learn from the great smog of 1950s in London. Sustainability, 6(8), pp.5322-5338.

[20] Zhu, J.; Dolgov, D.; Ferguson, D. Methods and Systems for Detecting Weather Conditions Including Fog Using Vehicle Onboard Sensors. U.S. Patent US8983705B2, 17 March 2015.

[21] McCall, B. and Vodrazka Jr, W.C., 1997. *States' successful practices weigh-in-motion handbook* (No. FHWA-PL-98-019; HPM-30/2-98 (750) QE; 1998-437-826/90009). United States. Federal Highway Administration.

[22] Brooke, Lindsay. (2020) Ultrasonics to keep lidar clean. Available at: https://www.sae.org/news/2020/11/ultrasonic-cleaning-for-lidars

[23] Caltrans Division of Research, Innovation and System Information, Ensuring Accuracy of Roadway Surface Condition Sensors, Ian Turnbull, Caltrans Office of ITS Engineering and Support, June 1, 2016, Produced by CTC & Associates LLC

[24] Krishnan, V. (2019) Self Driving Bugaloo: How Ford is Keeping Autonomous Car Sensors Squeaky Clean. Available at: https://medium.com/self-driven/self-driving-bugaloo-how-ford-is-keeping-autonomous-car-sensors-squeaky-clean-43b2c5382061

[25] Puts, M.J., Daas, P.J., Tennekes, M. and Blois, C.D., 2018. Using huge amounts of road sensor data for official statistics.

[26] LIDAR sensor simulation in adverse weather condition for driving assistance development.

[27] Chang, C.F., Wu, J.L., Chen, K.J. and Hsu, M.C., 2017. A hybrid defect detection method for compact camera lens. Advances in Mechanical Engineering, 9(8), p.1687814017722949.